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Applicability of UAVs as a tool for municipal environmental monitoring

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Tiivistelmä - Referat - Abstract

Kuntien ympäristöviranomaiset ovat velvoitettuja suorittamaan ympäristövalvontaa. Miehittämättömät ilma-alukset (droonit) voivat helpottaa ympäristövalvontaa mutta niiden soveltuvuutta kunnallisen ympäristövalvonnan työkaluksi ei ole tutkittu. Tässä työssä tarkasteltiin, miten kunnat ovat käyttäneet drooneja, ja testattiin droonien soveltuvuutta ympäristövalvontaan ja tarkastustyöhön roskittumisen seurantaa esimerkkinä käyttäen.

Tutkimuksen ensimmäisessä osassa Suomen kuntien ympäristöviranomaisille, Ruotsin kunnille ja Eurocities WG Waste -ryhmään kuuluville kunnille (n = 512) lähetettiin kysely, jossa kysyttiin droonien käyttösovelluksia, käytön tiheyttä, onnistumisastetta, epäonnistumisten syitä ja tulevaisuuden suunnitelmia. Kyselyn tulokset analysoitiin kuvailevan tilastoanalyysin avulla. Tutkimuksen toisessa osassa droonia käytettiin roskamonitorointitutkimuksessa neljässä kohteessa Helsingissä. Otetuista droonikuvista laskettiin visuaalisen havainnoinnin avulla roskat kategorioittain ja lehdet. Droonikuvahavainnoinnin tarkkuutta arvioitiin vertaamalla havaittujen roskien lukumäärää maastossa tehtyyn roskien laskentaan. Yhdessä kohteessa droonikuvahavainnointia teki myös kontrolliryhmä. Sen tarkoitus oli mitata tulosten vääristymää, joka syntyy, kun sama yksilö suorittaa sekä maastotutkimukset että laskennat kuvista. Tulosten tilastolliseen analysointiin käytettiin Wilcoxonin merkittyjen sijalukujen testiä ja Cronbachin α -reliabiliteettitestiä.

Kyselyn osallistumisprosentti oli alhainen, 3,7 % (n = 19). Käytettyjen sovellusten kirjo oli laaja ja painottui sovelluksiin, joissa droonia oletettavasti ohjataan manuaalisesti. Käyttö oli erittäin onnistunutta. Tärkeimmät epäonnistumisen syyt olivat säätekijät sekä tietotaidon puute. Droonit olivat osa valtaosan tulevaisuudensuunnitelmia. Roskamonitorointitutkimuksessa suoritettujen droonikuvahavainnointien tarkkuus maastotutkimukseen verrattuna oli 90,5 % vain roskat ja 87,5 % myös lehdet huomioiden, eivätkä droonikuvahavainnoinnit ja maastotutkimukset erinneet toisistaan tilastollisella merkitsevyydellä. Etenkin lehdet osoittautuivat haastaviksi havaita kuvista. Kontrolliryhmän havainnointitarkkuus verrattuna maastotutkimukseen oli 67,9 % vain roskat ja 49,0 % myös lehdet huomioiden, jolloin kontrolliryhmän ja maastotutkimuksen tulokset erosivat tilastollisella merkitsevyydellä (p = 0,028). Kontrolliryhmän sisäinen reliabiliteetti oli suhteellisen korkea, α = 0,776 ilman lehtiä ja α = 0,805 lehtien kanssa. Tulosten perusteella droonit ovat tarpeeksi tarkkoja ja sovelluksiltaan monipuolisia sopiakseen kunnallisten ympäristöviranomaisten valvonta- ja tarkastustyökaluiksi. Drooneilla on kyky täydentää maastokäyntien havaintoja tai tietyin edellytyksin jopa korvata ne itsenäisenä havainnointimetodina. Sovellusten ja havainnonititapojen kehitystyölle sekä jatkotutkimukselle droonien käytöstä kunnissa on lisätarvetta.

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Tiivistelmä - Referat – Abstract

Municipal environmental authorities are required to conduct environmental monitoring. Unmanned aerial vehicles, UAVs, may be helpful in environmental monitoring but their applicability as a tool for municipal environmental monitoring has not been studied. In this thesis it was studied, how municipalities have been utilizing UAVs. Additionally, UAVs applicability for environmental monitoring and inspection work was tested using a litter monitoring experiment as an example.

In the first part of the study, a questionnaire was sent to municipal environmental authorities in Finland, to municipalities in Sweden and to those participating in Eurocities WG Waste group (n = 512), covering the used applications, their utilization frequencies and successfulness, reasons for failures and future plans. The results were analyzed using descriptive statistics. In the second part of the study, a UAV was utilized in a litter monitoring experiment on four sites in Helsinki. Litter by category and leaves were counted based on visual observations from UAV imagery. The accuracy of UAV imagery detection was assessed by comparing its and ground assessment (GA) results. On one site, a control group also carried out UAV imagery detections in order to assess the magnitude of bias or offset occurring when both the GA and the litter detection from UAV imagery are conducted by a single individual. The Wilcoxon signed rank and Cronbach's α reliability tests were used for statistical analysis of the results.

Response rate of the questionnaire was low, 3.7% (n = 19). The pool of used applications was extensive and covered a variety of monitoring and inspecting targets with emphasis on the presumably manually piloted applications. Utilization was very successful. The most important reasons for failures were poor weather followed by lack of information and expertise. UAVs were included in the future plans of most participants for municipal environmental monitoring purposes. The UAV imagery detection accuracies of litter and leaves compared to the GA results were high, 90.5% for litter and 87.5% for litter and leaves, and no statistically significant differences existed between the assessment results. Especially leaves proved challenging to detect from UAV imagery. The control group's detection accuracies were 67.9% without and 49.0% with leaves, and with leaves the results differed with statistical significance (p = 0.028). The internal reliability of the control group was relatively high, $\alpha = 0.776$ without and $\alpha = 0.805$ with leaves. UAVs are deemed sufficiently accurate and versatile as monitoring and inspecting tools for municipal environmental authorities. They have the capability to complement ground assessments or, with certain prerequisites, even function as an independent monitoring method. Further application and detection method development and research on municipal UAV utilization are needed.

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Abbreviations

UAS	Unmanned aerial system
UAV	Unmanned aerial vehicle
AOI	Area of interest
POI	Point of interest
GSD	Ground sampling distance
VLOS	Visual line of sight
BVLOS	Beyond visual line of sight

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1 Introduction

The term environmental monitoring can be defined as observing and studying the environment with the intent of collecting data. This data can then be applied to create knowledge of the subject of monitoring for our better understanding of it (Artiola et al. 2004). Reasons for conducting environmental monitoring may be the intrinsic value of knowledge or more concrete reasons, such as creating information for decision-making. From the municipalities' perspective, the environment must be monitored to prevent its degradation and contamination (City of Helsinki 2019). Lovett et al. (2007) argue environmental monitoring to be an important field of science, creating far-reaching benefits for society. It creates knowledge for local policymakers and is essential for environmental protection efforts. They also remind that environmental monitoring ensures the well-being of inhabitants and natural habitats.

Various methods of collecting data from the environment may be utilized in environmental monitoring spanning from fieldwork observations and sample collection to satellite imagery in order to obtain relevant and necessary information (Kim & Platt 2008; Artiola et al. 2004). Often multiple complementing methods are used simultaneously. Conducting a ground assessment (GA) on the area of interest (AOI) enables detailed assessment conduction. Close-up photographs may be taken and sources of pollution such as noise alongside with discharges of chemicals and wastewater may be observed. This method has high temporal resolution, i.e. the time between observations is short, given that there is sufficient workforce available for frequent visits on the site. Conducting a ground assessment requires a minimal number of technological instruments and technological expertise from the user, apart from the use of a photo documenting and necessary measurement tools, such as a sound level meter. However, ground assessments conduction can be time-consuming (Martin et al. 2018). This can be the case especially if the area of interest is large or terrain difficult and the area requires an overall assessment rather than an inspection of a specific detail.

While aerial photographs from planes and satellite imagery offer great spatial coverage, their temporal and spatial resolutions, i.e. how detailed the imagery is, are too low to fulfil all needs of environmental monitoring. They are useful for monitoring targets of a larger scale, such as agriculture, vegetation, or urban growth, but ineffective for monitoring smaller AOIs or individual sites (Manfreda et al. 2018). Aerial photographs have their spatial resolutions typically in tens of centimeters (Tuominen & Pekkarinen 2005). For instance, aerial imagery with a pixel size of 0.25 m and temporal resolution of 3–10 years is only available for parts of Finland in Geodata portal Paikkatietoikkuna (2021). At best, available aerial imagery reaches pixel sizes of 0.05 m, but is limited to central Helsinki area with a 1–2-year temporal resolution (Helsinki Map Service 2021). Meanwhile, free of charge satellite imagery from widely used Sentinel and LANDSAT satellites have spatial resolutions of 10 and 15 meters (panchromatic band) at best, respectively (ESA 2021; USGS 2021). However, above-ground photographs from planes or satellite imagery may still be utilized e.g. in forms of maps while preparing for a ground assessment, although their own resolutions might not be sufficient for conducting an independent assessment or inspection. Such imagery overlapped with a city plan, property outlines, or some other dataset supports the GA conduction by giving insight to the AOI.

The limitations of these conventional environmental monitoring methods have opened a new niche for a more versatile and flexible environmental monitoring tool for municipal environmental monitoring. Easy to use, versatile, and affordable drones have gained popularity and are inching in to fill this niche.

Drone is a term commonly used in general discussion to describe any relatively small aircraft flying without an onboard pilot, although drones are not limited to aircrafts and also include land and aquatic vehicles, such as remote-control submarines (Austin 2010; Salazar et al. 2019). The actual flying devices without an onboard pilot are referred to as unmanned aerial vehicles (UAVs), which in turn are a part of an unmanned aerial system (UAS). In addition to the UAV, a UAS contains the payload, control stations and supportive systems, launch and recovery installations, and other sub-systems (Austin 2010). Therefore, it is important to distinguish between the terms and realize, that the true meaning of term “drone” is dependent on the context.

During the last decade, the costs of UAVs and data post-processing softwares have reduced significantly whilst new applications of use are constantly being developed and adopted (Manfreda et al. 2018). UAV utilization has also proven cost-efficient. According to Matese et al. (2015), who compared the costs of UAV, airborne and satellite imagery acquisition, airborne systems become more economical than UAVs when the AOI reaches a size between 5 to 50 hectares. Another study puts the cost-efficiency threshold of UAV assessments to < 20 ha (Manfreda et al. 2018). Commercially available UAVs are also relatively affordable, as their prices start from just above 100 € and many professional-grade UAVs cost ca. 1000–3000 €, though some have a price tag of well over 10,000 € (DJI 2021; Feist 2021a). Notable is also that the maintenance cost of a UAV is negligible.

As drones and especially UAVs have become more available on the market and their prices affordable, the interest towards them as also grown. De Miguel Molina & Segarra Oña (2017) analyzed the market and industry sector of aerial drones and projected growth in all user categories from hobbyists to governmental organizations. Additionally, a self-proclaimed information portal Unmanned Airspace (2018) reports that 39 cities around the world are pioneering urban UAS operations consisting predominantly of security and various delivery systems. Traficom (2020a) expected there to be up to ca. 50,000 UAS operators in Finland in the beginning of 2020, most of whom at the time were unlicensed hobbyists. The single largest UAS operator in the country is the Police of Finland who in 2019 already had nearly 400 trained UAV pilots and over 160 unmanned aerial systems (Nurmi 2019; Lentoposti.fi 2019).

Public organizations other than those working in the public security sector are also interested in the possibilities of UASs. For instance, a pilot experiment on first responder transportation via UAVs to remote locations is underway in Helsinki (Jompero-Lahokoski 2021). However, little to no official statistics exist on UAV utilization in Europe and the extent of municipal UAV utilization especially for environmental monitoring purposes in Finland is currently unknown.

The Finnish municipal environmental authorities have a legislative obligation to conduct environmental monitoring within their respective municipalities (HE 2013/214 § 167). This obligation penetrates all sectors of society and includes monitoring of public parks, businesses, industrial sites, and in some cases even personal properties of individuals. For instance, in Helsinki, various divisions within the municipal organization carry out environmental monitoring on their specific fields of responsibilities, such as the Urban Environment Division. They monitor the environment for any violations of e.g. the municipal environmental protection regulations.

Visits to the AOIs and carrying out ground assessments is currently the only conclusive monitoring method for municipal environmental authorities in many cases**.** This method enables them to verify that activities on the site are conducted in accordance to regulations. UAVs have been found to be much quicker in assessing an AOI compared to a GA (Martin et al. 2018) and their utilization could save time for municipal officials, ultimately reducing personnel costs for municipalities.

Additionally, UAV utilization has been described to increase worker safety on construction sites since UAVs can be used for many risky tasks, such as monitoring sites with busy traffic and inspecting tall structures and other targets that are difficult to reach (Howard et al. 2017). The same applies for the municipal officials while monitoring or inspecting challenging and possibly hazardous AOIs such as landfills or junkyards. In such cases the ability to assess the site from above from many different angles may prove vital, since UAV utilization could eliminate the need for a ground assessment and thus decrease the risk of injuries.

Apart from UAVs, only aerial photographing could provide accurate enough data with a quick enough response time for many of the monitoring tasks of municipal environmental authorities. However, having an aircraft and a pilot on continuous standby is out of economical reach of many municipalities. On the contrary, a UAV may be deployed where and whenever needed. UAV utilization does, however, have its legal limitations. Laws and regulations considering UAV utilization in Finland are summarized in Appendix 1. For instance, operating a UAV generally still requires the pilot to maintain a visual line of sight (VLOS) to the aircraft (Traficom 2021), especially if the UAV is used rather spontaneously based on the need on site. This essentially forces the inspector to visit the AOI. A UAS can still help to reduce the time spent on the site and offers greater flexibility to monitoring methods.

UAVs have many suitable qualities for municipal environmental monitoring. They are nimble, allowing them to be used to photo document both relatively small AOIs as well as large ones, up to the neighborhood scale (Manfreda et al. 2018; Matese et al. 2015). Their temporal resolution is comparable to ground assessments and their spatial resolution is much greater than other above-ground solutions as UAVs in typical monitoring use reach spatial resolutions of ca. 1 cm/pixel, often even < 0.5 cm/pixel (Andriolo et al. 2020; Fallati et al. 2019; Martin et al. 2018; Merlino et al. 2020).

A limited amount of previous literature is available on direct municipal UAV utilization, but the literature does cover a variety of topics. As mentioned earlier, UAVs have high potential in the public safety sector (Taylor et al. 2016). It has been suggested that UAVs may be helpful in search and rescue operations due to their versatility and maneuverability despite the difficulty of terrain (Van Tilburg 2017; Weldon & Hupy 2020). Gasperini et al. (2014) obtained UAV imagery of a municipal landfill to estimate its volume and surface subsidence and concluded that UAV-based results were as accurate as conventional methods while UAV utilization offered more flexibility. Digital terrain models generated from UAV imagery have been used to study landfill waste-slides (Savchyn & Lozynskyi 2019; Nikulishyn et al. 2020). UAV imagery and elevation measurements were utilized to study landfill surface temperatures with new methods by Hernina et al. (2020). Landfill settlement characteristics have been studied by Baiocchi et al. (2019), who concluded UAV measurements to have comparable accuracy to e.g. LIDAR measurements. Capabilities of a UAV for land use and land cover monitoring have been studied by Pedras et al. (2015). UAV imagery sequences of roadside green belts have been studied for more precise maintenance and monitoring by Duan et al. (2019). New methods for pavement management systems have been studied by Garilli et al. (2021), who found UAV photogrammetry-based solutions to offer viable alternatives for conventional inspection methods. UAVs have been used for monitoring the structure and movement patterns of landslides in urban areas by Godone et al. (2020) and Sestras et al. (2021), who found UAV-based imagery and measurements useful. UAVs have also been found to be able to provide decimeter-level accuracy in monitoring mine tailings in Sub-Arctic conditions (Rauhala et al. 2017).

One of the more researched topics in UAV utilization is litter detection. However, previous literature is mostly limited to litter detection on beaches. In their studies, Bao et al. (2018), Fallati et al. (2019) and Martin et al. (2018) found UAVs to be efficient tools for anthropogenic marine debris detection. UAVs also offer detailed litter monitoring possibilities with minimal disturbance to the site (Andriolo et al. 2020; Merlino et al. 2020). Additionally, Hengstmann & Fischer (2020) studied the sources of macroplastics on beaches of a freshwater lake and used a UAV for plastic detection. While litter detection on beaches has been studied quite extensively, little to no litter detection studies have been conducted in other environments, which this thesis work in part aims to correct.

Several recent studies suggest that litter detection from UAV imagery via visual screening is a viable post-processing method. Fallati et al. (2019) made a comparison between litter detection via manual screening of images and deep learning and found image screening to have an accuracy of over 87%, whereas an artificial intelligence had results varying from 54% to 94% depending on the sunlight conditions. In another study, manual image processing was found to be ca. 62% accurate, although objects smaller than 4 cm in a linear dimension were not reliably detected from UAV imagery (Martin et al. 2018). A machine learning algorithm produced an abundance of false positives, resulting in an overestimation of five times the actual amount of litter. According to Martin et al.

(2018), these overestimations can be corrected with algorithm improvements and iterations and thus show upscaling potential for the future. They also found the UAV to be 39 times faster in monitoring their 325-meter long study area compared to a ground assessment. Merlino et al. (2020) reported that while larger items have a detection percentage of 85–100%, small objects, such as bottle caps, have a detection rate of only ca. 15% from UAV imagery obtained from a comparably very low altitude (6 m).

UAVs do, however, have their obvious drawbacks. Both flying a UAV and post-processing of the imagery with a suitable software do require some technological expertise from the user. Additionally, most UAVs cannot operate in rain, strong winds, or low temperatures, thus limiting their utilization opportunities (Manfreda et al. 2018), although there are some waterproof UAVs available (Feist 2021b). While strong winds might not necessarily lead to crashes, they severely compromise the platform stability, thus disturbing e.g. altitude control, sensor orientation, and spatial relation of UAV data to reality (Von Bueren et al. 2015). It is currently unknown what are the greatest and most common obstacles of UAV utilization in municipal environmental monitoring and whether they are due to drawbacks of UAVs themselves or some other reasons.

2 Research objectives and questions

The preceding scientific literature lacks knowledge in UAV utilization for municipal environmental monitoring. Finding out how well UAVs perform in monitoring tasks adds valuable knowledge for municipal authorities to exploit in their work. The objective of this master's thesis was to evaluate if (1) the practical applications of UAVs are versatile enough and (2) UAVs are sufficiently accurate for monitoring and inspection assignments for them to be applicable tools for municipal environmental authorities in their work. To address the research objective, two research tasks were conducted, both of which answering to specific research questions.

First, a questionnaire on UAV utilization in environmental monitoring was sent to municipal environmental authorities in Finland, Sweden, and elsewhere in the EU. The questionnaire was used to answer the following research question: How have UAVs been utilized in municipal environmental monitoring?

Second, a litter monitoring experiment was carried out to answer the following research question: How do assessments from UAV imagery compare in accuracy to ground assessments, municipal environmental authorities' currently often only conclusive monitoring method?

Combining the firsthand utilization experiences of municipalities and the observed assessment accuracies of UAVs will allow conclusions to be drawn of the applicability of UAVs for municipal environmental monitoring.

3 Materials and methods

An online questionnaire on UAV utilization in municipal environmental monitoring was used to collect information from Finnish, Swedish and other European municipalities considering their past, current, and future use of UAVs. Several AOIs situated in Helsinki were chosen for a litter monitoring experiment, for which UAV imagery was captured and ground assessments conducted. All data for this study was collected between September and November of 2020, including the questionnaire, UAV flights, and ground assessments. All dates presented in this thesis work follow the format commonly used in Europe (DD.MM.YYYY).

3.1 Questionnaire on UAV utilization

Unawareness of the state of UAV utilization in municipalities for environmental monitoring purposes creates interest to study how commonly and to which applications UAVs have been utilized across municipalities, and to which ends. Firsthand experiences of participants are hoped to expose most promising applications for municipal environmental monitoring. Also, surveying the future prospects of participants is hoped to give concrete indications of whether or not the UAVs are seen as a promising novel technology for environmental monitoring or rather a passing curiosity.

The E-form platform (E-lomake in Finnish) of the University of Helsinki provided by Eduix Oy was used to construct the questionnaire. The virtual questionnaire was sent to potential participants on October 5th, 2020 via corresponding email lists with a deadline for answering of two weeks. Two rounds of reminders emails were sent and the report on the results was offered as an incentive for all participants.

The questionnaire was sent to environmental authorities of 149 Finnish municipalities and to all 290 Swedish municipalities. This sample of Finnish environmental authorities was reached via an email list provided by Association of Finnish Municipalities (Kuntaliitto in Finnish). Additionally, questionnaire was sent to Eurocities WG Waste group with 82 member municipalities, nine of which overlap with the other two email lists. Therefore, there were a total of 512 individual recipients. Climatological, socioeconomical, and technological conditions in Sweden are comparable to those of Finland and therefore Swedish municipalities make fine potential participants to broaden the sampling group for finding applications that may also be utilized in Helsinki and other Finnish municipalities. Eurocities WG Waste group on the other hand provides Europe-wide sampling of municipalities with varying conditions. Together these participant groups provide a wide base of experience and knowledge on which application applicability and future prospects may be reflected upon.

The questionnaire consisted of multiple-choice questions, open questions, and one numerical value question. Each participant was asked to state their country and municipality as well as whether they utilize a UAV for environmental monitoring purposes. Separate questions were developed for both users and non-users. For non-users, questions included reasons for not utilizing a UAV as well as their future plans considering UAVs. For users, frequencies of use for several applications such as litter monitoring, weather monitoring, forest management, inspection work, etc., were surveyed. Users were also asked to rate their successfulness for each used application. Additionally, reasons for failures were surveyed alongside with plans for the future. The full questionnaire form can be seen in Appendix 2.

The multiple-choice, numerical value, and open questions were all analyzed using descriptive statistics. Statistical analysis tools could not be utilized due to a low number of participants, which in some questions was as low as six. Overall, 3.7% (19) of the recipients of the questionnaire submitted an answer.

3.2 Litter monitoring experiment in Suvilahti, Toukola, Viikki and Kyläsaari

All of the AOIs were assessed through a ground assessment and manual litter detection from UAV imagery. For clarity, litter and leaf assessments conducted from the UAV imagery by the UAV pilot and ground assessment conductor are referred to as UAV imagery detection. Furthermore, “litter” refers to objects of anthropogenic origin, such as bottle caps, and “items” covers both leaves of natural origin and litter.

The UAV utilized in this study was a DJI Mavic 2 Zoom quadcopter, equipped with a gimbal-mounted 12-megapixel RGB-camera producing 4000 × 3000-pixel images. The takeoff weight of the quadcopter is 905 g, it has a maximum flight time of 31 minutes, and a maximum wind speed resistance of 29-38 kph (ca. 8-10.5 m/s). The flight missions were carried out using Pix4Dcapture flight planning tool on the DJI Smart controller. Before the actual flight campaigns, practice flights were conducted. During these flights, different objects were situated on a test area and the area was photographed from several altitudes to find the best flight parameters for object identifying. Simultaneously, use of the flight planning software Pix4Dcapture was practiced.

3.2.1 Flight parameters

Previous studies with comparable UAV utilization have used varying parameters for flight missions and the mission parameters for this study were selected based on their experiences as well as on the practice flights. For the sake of consistency, all flight missions used the same flight parameters excluding the mission in Viikki.

A flight altitude of 10 meters was selected, resulting in a ground sampling distance (GSD) of 0.23 cm/pixel. The selected altitude is the lowest possible and results in the best spatial resolution available with the flight mission planner tool utilized. For reference, Merlino et al. (2020) and Fallati et al. (2019) opted to have GSDs of 0.18 cm/pixel and 0.44 cm/pixel for their comparable studies, respectively.

A continuous flight at a constant velocity of 0.9 ± 0.1 m/s was chosen for this study. In the flight mission tool this is the fastest velocity option for the selected altitude. This option reduces flight time, which is limited by the battery capacity, yet produces accurate images and reduces inspection time. In previous literature, Merlino et al. (2020) used the “stop and go” mode also available in the quadcopter utilized for this study in order to avoid blurriness of images at the altitude of 6 meters. On the contrary, Fallati et al. (2019) opted for a continuous flight with a constant velocity of 1.3 m/s and Martin et al. (2018) for a constant velocity of 2 m/s both at 10-meter altitude.

The gimbal-mounted camera was set to nadir (camera pointed straight down towards Earth’s center), 90 degrees downwards. An image overlap of 80% from the possible range of 70 to 90% was selected (Andriolo et al. 2020; Bao et al. 2018; Fallati et al. 2019; Merlino et al. 2020), as it was deemed sufficient enough for orthomosaic construction while saving the post-processing procedure from becoming unnecessarily heavy to compute.

3.2.2 Role of weather

Since weather plays an important role in UAV utilization, weather data is provided for each UAV flight in Appendix 3. The data was obtained through the Finnish Meteorological Institute’s website’s “Download observations” service, which allows free access to weather data (FMI 2021). These observations include cloud amount, air temperature, horizontal visibility, and wind speed and direction, to name a few, all measured in 10-minute intervals. The weather data, while not systematically analyzed, is considered as a factor while discussing the results of the litter monitoring experiment.

3.2.3 Area descriptions

Four AOIs were chosen for the litter monitoring experiment (Table 1). The foreground of a graffiti fence in Suvilahti (Figure 1) was chosen as the main AOI of the monitoring research due to its favorable qualities. Multiple events, concerts and festivals typically take place in Suvilahti each year, but in 2020 it has mainly been open for light traffic as a passthrough way from Kalasatama, Mustikkamaa and Korkeasaari Zoo to Sörnäinen.

Table 1.
Locations, assessment dates and surface areas of each four AOI chosen for the litter monitoring experiment, number of squares or slices, their sizes, and their total surface areas for Suvilahti and Vikki AOIs. In Suvilahti only the contents of the litter squares were assessed. Other AOIs were assessed in their entirety. Viikki AOI was segmented into slices and the slices cover the entirety of the AOI. Both the ground assessments and the UAV flights were conducted on the given dates. Squares assessed on 13.10. in Suvilahti were randomized. Segment identification G refers to gravel background and A to asphalt.

Description / AOI	Location (latitude, longitude)	Assessment date	Segment	Surface area (m2)	Number of squares / slices	Square size (m)	Total surface area of squares / slices (m2)
Suvilahti	60.110790, 24.581596	02.10.	G1	48	5	1 × 1	5
		13.10.	G1	48	13	0.5 × 0.5	3.25
			G2	40	7	0.5 × 0.5	1.75
			A1	40	15	0.5 × 0.5	3.75
Suvilahti total				176	40		13.75
Toukola	60.120860, 24.584280	14.09		1830			
Viikki	60.132879, 25.004164	05.11		495	8	5 × 11	495
Kyläsaari	60.113800, 24.584025	06.11		62.5			

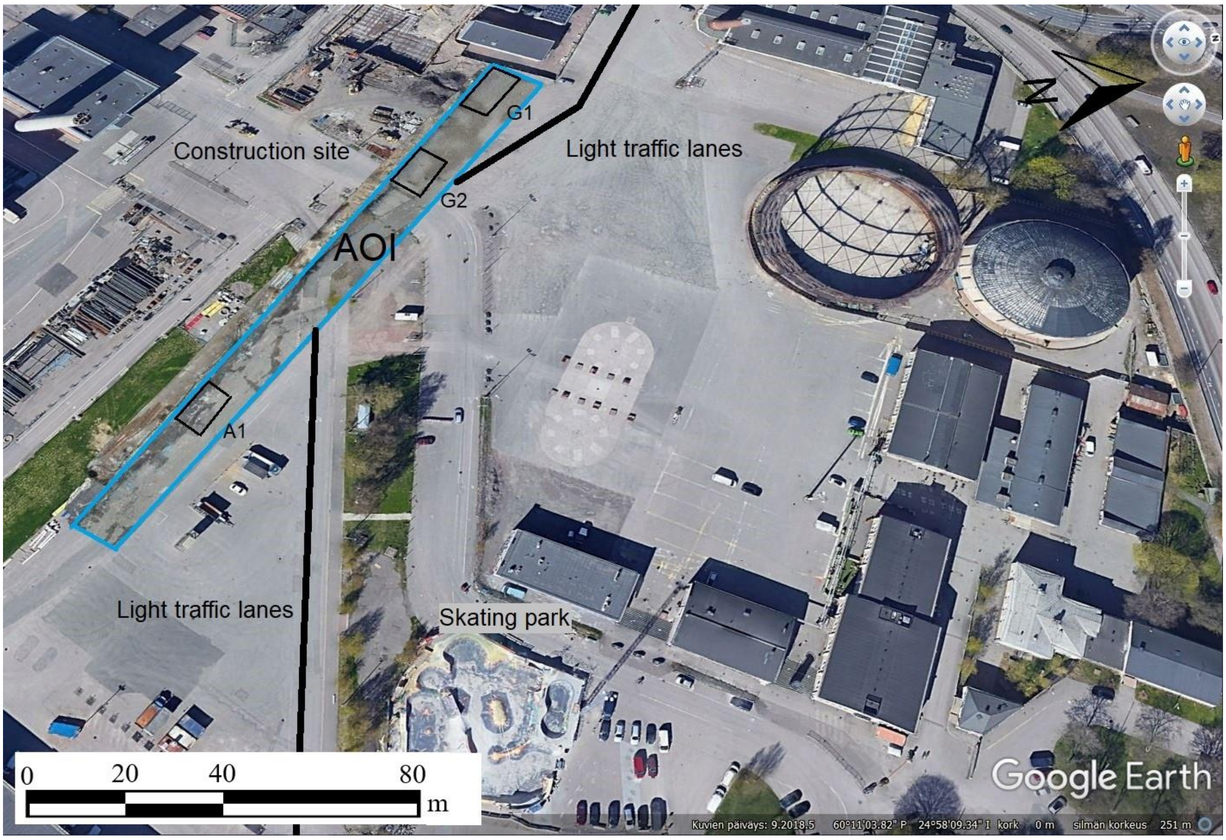

Figure 1. Suvilahti AOI (outlined in blue) of the litter monitoring experiment. The AOI orthomosaic was generated with and automatically positioned by Pix4Dmapper on top of Google Earth -platform imagery. All rights of the background image belong to Google. Approximate locations of segments G1, G2, and A1 are outlined in black. Segment identification G refers to gravel background and A to asphalt. Black lines represent the approximate location of the light traffic road with lanes for both cyclists and pedestrians outside the AOI as it is not visible in the Google Earth footage. A construction site is located on the southern side of the graffiti fence. A popular skating park can be seen on the bottom of the figure.

A popular skating park is located less than 100 meters northeast of the east end of the AOI. The graffiti fence runs in the direction of northwest to southeast and the AOI is located on the northern side. The foreground is a flat plain consisting of both gravel and paved surfaces. This creates a possibility to study detection rates of litter on both surfaces from UAV footage of a single flight mission. Bypassing light traffic, users of the skating park, graffiti painters and the construction site on the south side of the fence might all be potential distributers of litter to the AOI. The foreground experiences frequent littering with various types of litter from spray paint cans to food packaging.

From the AOI running along the fence, three smaller segments were chosen for closer inspection due to their higher litter abundance and to represent different background surfaces. These three segments of the AOI were labeled as Gravel 1 (G1), Gravel 2 (G2), and Asphalt 1 (A1). G1 covers an area of 48 m^2 with dimensions of 12 m × 4 m, and G2 and A1 an area of 40 m^2 with dimensions of 10 m × 4 m each (Table 1). The first few meters of the foreground from the fence outwards are of the greatest interest as litter abundance decreased further away. Thus, the longer side of each segment runs along the fence. The three study areas were segmented into a grid consisting of 0.5 m × 0.5 m squares. Hence, G1 has 192 squares and G2 and A1 160 squares each, all of which were then assigned a number between 1 and 192 or 1 and 160, respectively. Twelve litter square locations were randomized for G1, seven for G2, and fifteen for A1 by using the random sampling method without replacement by utilizing an online number randomizer (Randomlist.com 2020). Random sampling without replacement was chosen since it offers smaller variance in a sample population with equal probabilities and in a finite AOI the possibly added work from sampling unique squares would not justify the increase of variance (Basu 1958). Furthermore, a higher number of unique squares offers more possibilities for different litter varieties to occur. However, while marking the assigned squares on G1, a measurement error occurred and square #9 was misplaced 0.5 meters closer to the fence than supposed to. In order to maintain continuity with the originally randomized squares and as the site was already disturbed, a new square (#13) was created in the misplaced square. Locations of squares within all segments can be seen in Fig. 2. A rectangular flight mission plan covering all three segments was drawn with Pix4Dcapture-software over the AOI (Fig. 3). On G2, seven square locations were randomized in order to bring the total of squares on gravel to twenty. The total number of 0.5 m × 0.5 m litter squares is therefore 35 (Table 1).

In addition to randomized squares, a set of five 1 m × 1 m litter squares (Fig. 4) was recorder 11 days earlier on a separate flight mission with the same ground assessment methods and UAV flight parameters as the 0.5 m × 0.5 m squares. However, the locations of these five squares were manually assigned within G1 to contain many different sizes and types of litter for a more applied approach for assessing the accuracy of the UAV footage and post-processing methods.

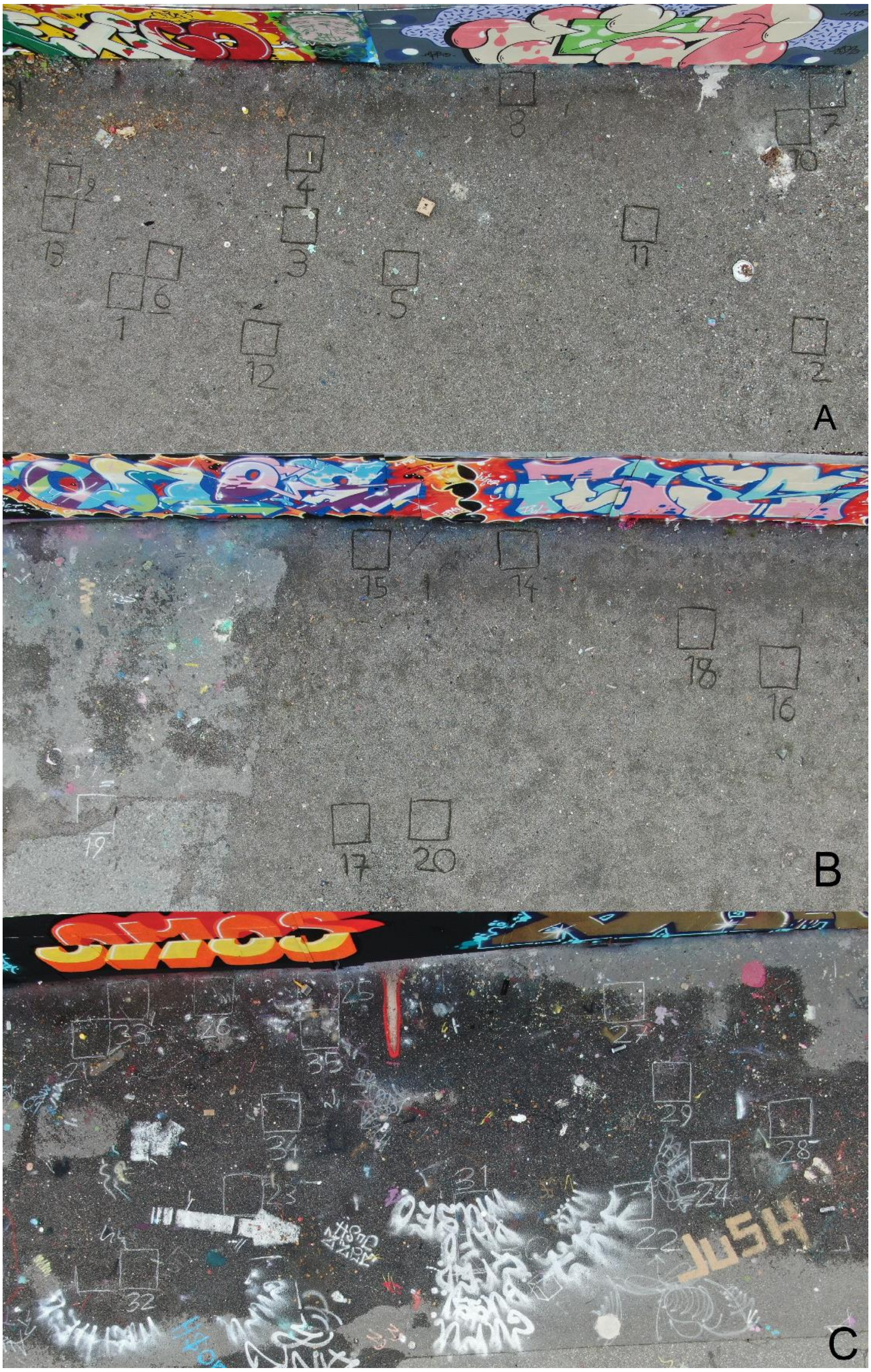

Figure 2. Segments G1 (A), G2 (B), and A1 (C) of Suvilahti AOI illustrating the randomized placements of the 0.5 m × 0.5m litter squares captured during the flight mission from an altitude of 10 meters for the litter monitoring experiment. Segment identification G refers to gravel background and A to asphalt. Initial misplacement of randomized square 9 (A) concluded in the manual addition of square #13 on G1.

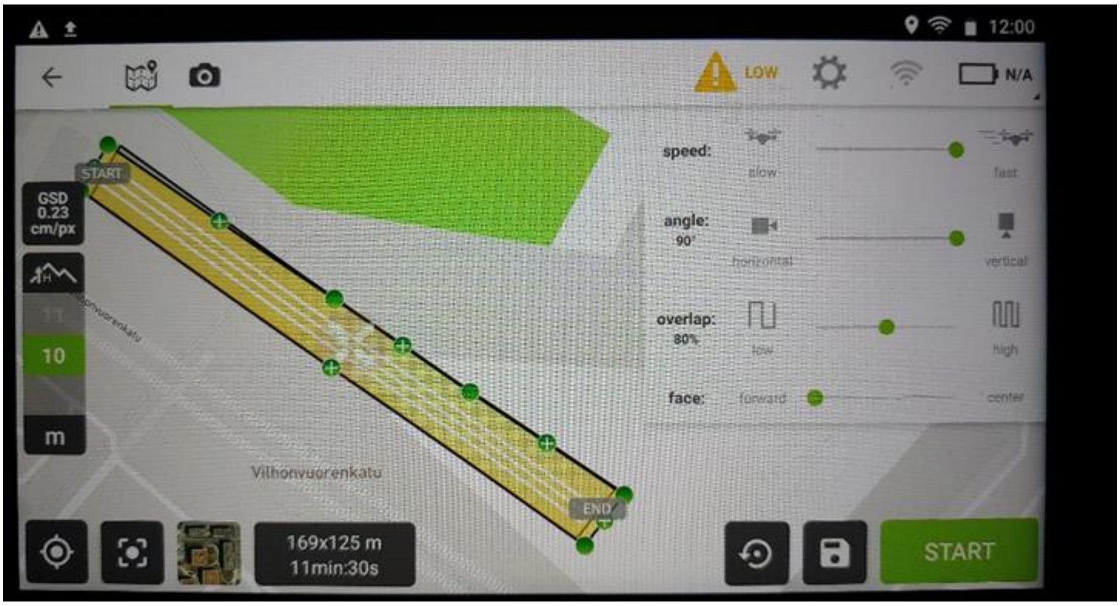

Figure 3. A picture taken of the DJI smart controller’s screen with Pix4Dcapture flight mission planning app open. Used flight parameters for the litter monitoring experiment flight mission in Suvilahti can be seen on the screen. The flight parameters were the same for all AOIs, excluding Viikki.

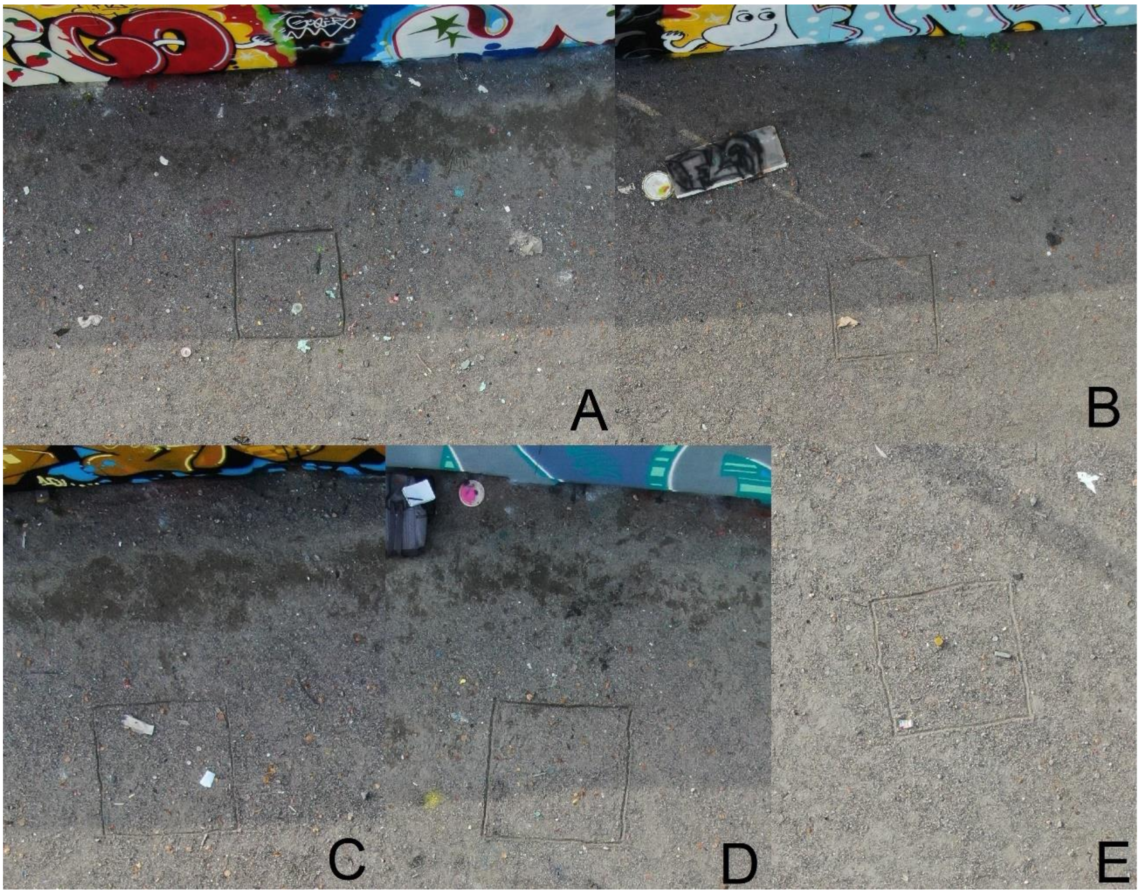

Figure 4. The five 1 m × 1 m litter squares (A-E) in manually assigned locations on segment G1 (gravel 1) in Suvilahti AOI of the litter monitoring experiment. These five squares were assessed eleven days prior to the randomized squares.

The second AOI was at the southern end of Toukola Park in Arabianranta (Fig. 5 A). In this AOI, a polygon flight mission with the quadcopter was conducted similar to the one conducted in Suvilahti. The main differences are the shape of the AOI and surface variability, as Toukola AOI contains grass, water, and a rocky shoreline. In order to avoid collisions with migrating geese flocks and unnecessary automated dodge action from the quadcopter while avoiding taller trees, a polygon with an approximate area of 1830 m^2 was drawn conforming the landscape, focusing on the shoreline of the park (Fig. 5 B). A ground assessment counting all litter was then conducted on the same area.

Figure 5. Toukola AOI of the litter monitoring experiment. A high-altitude image with the AOI approximately outlined in blue (A) and the parameters of the polygon flight mission in Pix4Dcapture-app (B). The flight mission deviates from a simple rectangle in order to capture a longer strip of the shoreline while avoiding tall trees next to park walkways.

The third AOI in Viikki represents varying surfaces, most importantly vegetation and autumn leaf cover (Fig. 6). The litter in the area was mostly generated when a temporary bus stop was located there still approximately a week prior to the assessments. A stretch of a light traffic lane and adjacent areas with vegetation with a combined area of 495 m^2 (45 m × 11 m, ± 0.5 m, ± 22.5 m^2) was photographed with the quadcopter. Two flights were conducted with parameters set to produce image overlaps of 90% and 80% respectively, and the flight speed was slightly reduced compared to the two preceding AOIs to ca. 0.8 m/s due to challenging wind conditions. A ground assessment was carried out, mapping all litter in the area. The area is limited by the roadside curb on one side and a runoff ditch on the other (Fig. 6). The AOI was segmented into 5 m long slices along the road to help with the assessments and data analysis. The water-filled ditch is considered a part of the AOI. The AOI consists of a strip of bare soil and grass between the road and the light traffic lanes with young trees of up to ca. six meters tall, the pedestrian and bicycle lanes themselves, a strip of unmanaged vegetation next to the ditch containing mainly vascular plants and bushy deciduous trees up to ca. four meters tall, and the water-filled ditch. As the AOI was photographed in early November, almost all leaves had fallen from the trees to the ground, although many had been blown away by a storm a few days prior to documentation.

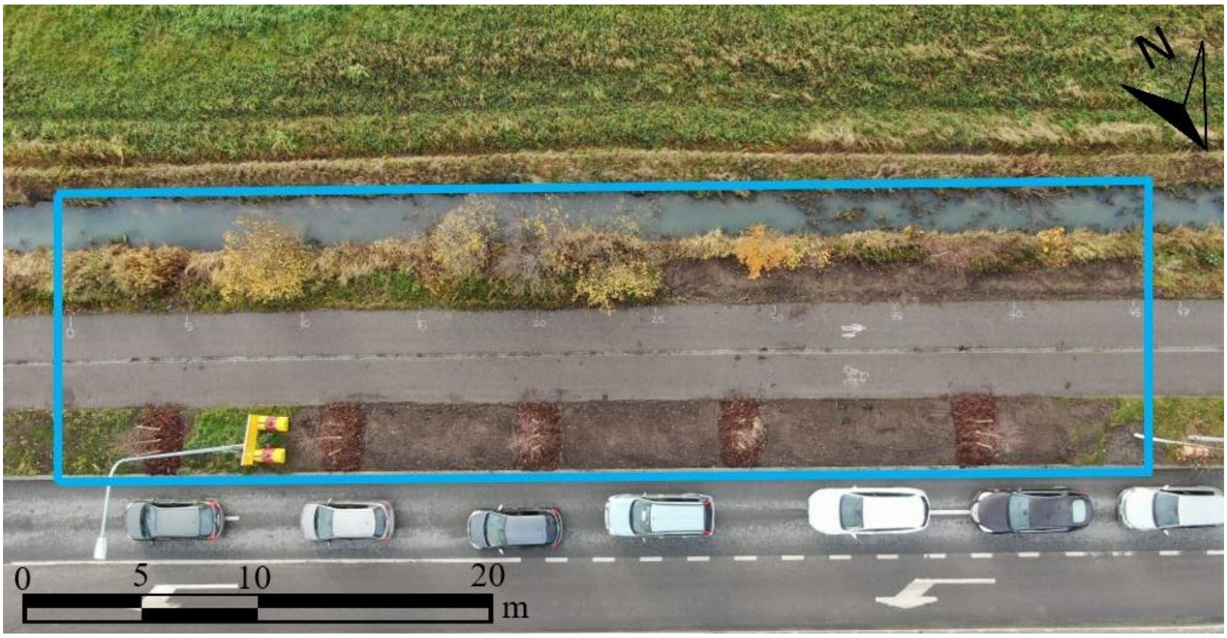

Figure 6. High-altitude photograph of Viikki AOI assessed for the litter monitoring experiment. The AOI is 45 meters long and is bordered by a roadside curb and the far side of a ditch as indicated by the blue outlines. A strip of bare soil with four newly planted trees indicates where a temporary bus stop was located a week prior to the assessments.

The fourth AOI, located between a city access road and a truck stop, was studied in Kyläsaari (Fig. 7). The area is under development and the sides of the truck stop experience accumulated amounts of litter. The shape of the AOI roughly resembles a trapezoid with the side lengths of 4.5 m, 10.0 m, 8.0 m, and 10.6 m, and an area of 62.5 m^2 (Table 1). Surface of the AOI consists of rocks and stones of varying sizes, gravel, and vascular plants up to ca. 0.5 m tall. The AOI was documented in its entirety with the quadcopter and litter was counted during a ground assessment.

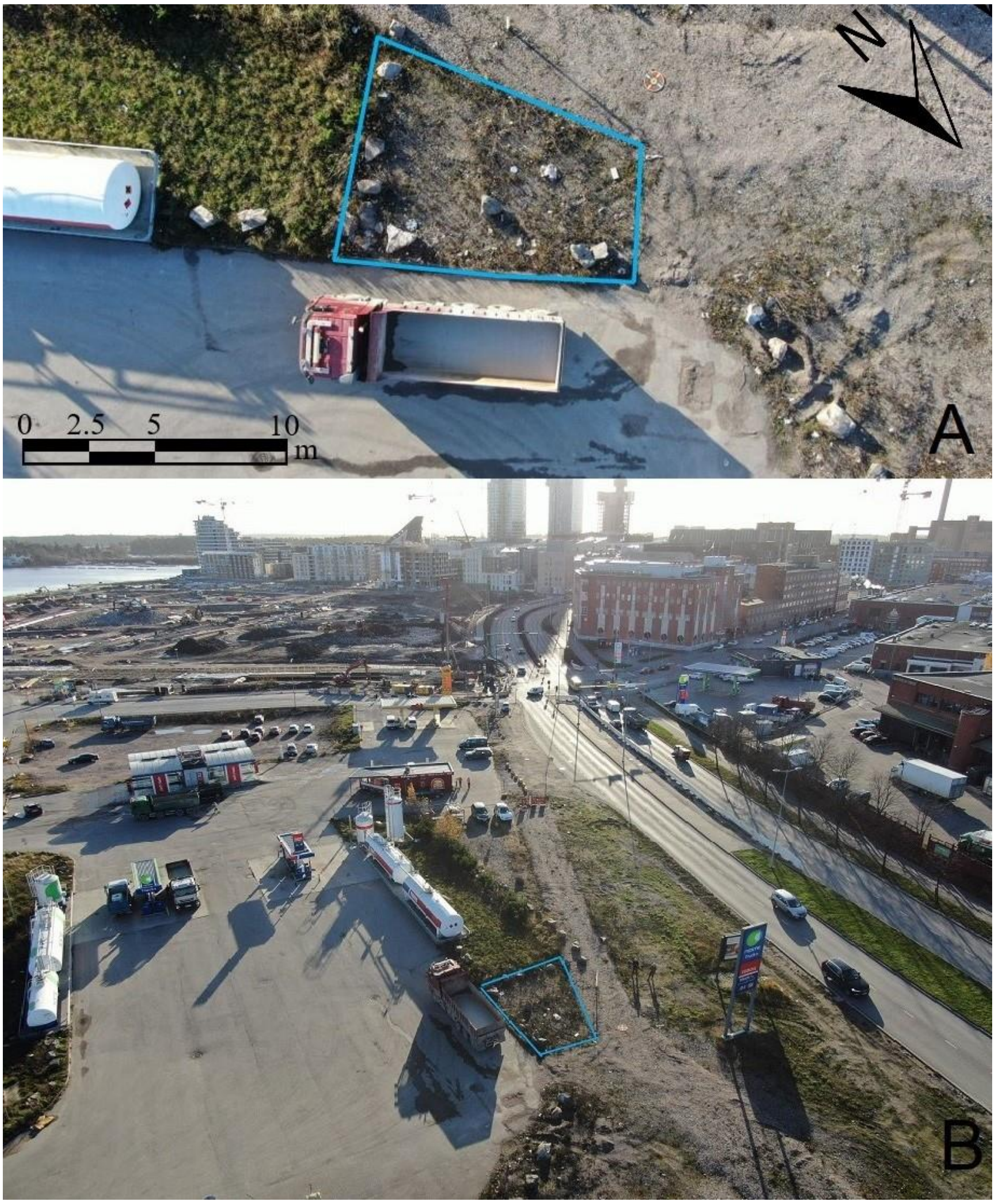

Figure 7. Kyläsaari AOI assessed for the litter monitoring experiment outlined in blue from above (A) and in its surroundings with Kalasatama district on the background (B). A truck stop with gas pumps and a fast-food kiosk is located in the proximity of the AOI.

3.2.4 Ground assessment and UAV imagery detection

A ground assessment was conducted on each AOI immediately after the flight mission but before the UAV imagery detection. Since the assessments were carried out during the autumn months, some additional details were to be considered. Namely, the AOIs contained varying amounts of fallen leaves. Although leaves are not litter per se, they may be considered as an equally valuable item for detection as human-generated litter of artificial origin. Thus, all litter and leaves within the litter squares of Suvilahti were counted and categorized based on visual observations. Leaves were included in both the GA and the assessment from UAV imagery, because while assessing the imagery it might be possible to mistake leaves for litter. Leaves were not counted in the other AOIs due to the sheer sizes of the AOIs, their vegetation cover, and leaf abundance. Counting leaves during a GA reliably and quickly enough before wind moves them to or from an AOI after a UAV flight mission would have been practically impossible. Detection efforts of leaves from both the GAs and the UAV imagery would also have been unreasonably time-consuming and laborious over the relatively large AOIs. Otherwise the ground assessments were carried out in the same manner in all AOIs.

The results of the ground assessments are considered to reflect the true litter amounts within the AOIs given the proximity of both the observer and the photo documenting tool. The photo documenting tool used for ground assessment is an LM-G710EM “LG G7 ThinQ” smartphone equipped with a 16MP Super Wide Angle (F1.9 / 107°) / 16MP Standard Angle (F1.6 / 71°) camera with a resolution of 4656 x 3492 pixels (LG.com 2020).

During UAV imagery detection, the UAV imagery was screened manually for litter essentially by identifying litter from an individual image at a time based on visual observations. In Suvilahti, only the squares were screened, and litter with leaves counted and categorized to the same categories as during the GA, and on other AOIs all litter within the area was counted. As both the ground assessments and assessments from UAV imagery were conducted by the same person, there is a danger of bias and increased accuracy in UAV imagery detection. To mitigate this offset, a minimum of two weeks was allowed to pass between the conduct of the ground assessment and the UAV imagery detection for each AOI.

3.2.5 Control group assessment

The magnitude of bias or offset produced via a single individual carrying out both the ground assessment and the imagery detection in an AOI was studied by presenting quadcopter imagery from Suvilahti to a control group of five volunteers and comparing their results to the UAV imagery detection results. The results of the control group were also directly compared to both the ground assessment and UAV imagery detection by subtracting the latter two individually from the control groups results. This gives a numerical value that describes how many more or less pieces of litter the control group detected. None of the control group members had been to the site for at least two months prior to the study, although one was familiar with the site and aware of its state considering litter beforehand.

Ten 0.5 m × 0.5 m litter squares from Suvilahti were purposefully selected for the control group assessment so that they represented various amounts and types of litter (Fig. 8). They also represent the three sections of Suvilahti AOI in relative proportions to the original dataset. Thus, four squares were selected from G1, two from G2, and four from A1. Each member of the control group was tasked to count the total amount of items in each square and classify them to the following ten categories: bottle cap, cardboard packaging, cigarette filter/bud, metal litter, paper litter, plastic litter, plastic packaging, unidentified, leaves, and other (please specify). These categories were most abundant in the GA and were also used for the UAV imagery detection for Suvilahti. The control group was given a general description of the area, similar to the Suvilahti AOI description given earlier, and instructions to count leaves and pieces of litter only the size of a bottle cap or cigarette filter and larger. A couple of squares that were not part of their assessment task were assessed together as practice before their independent assessments.

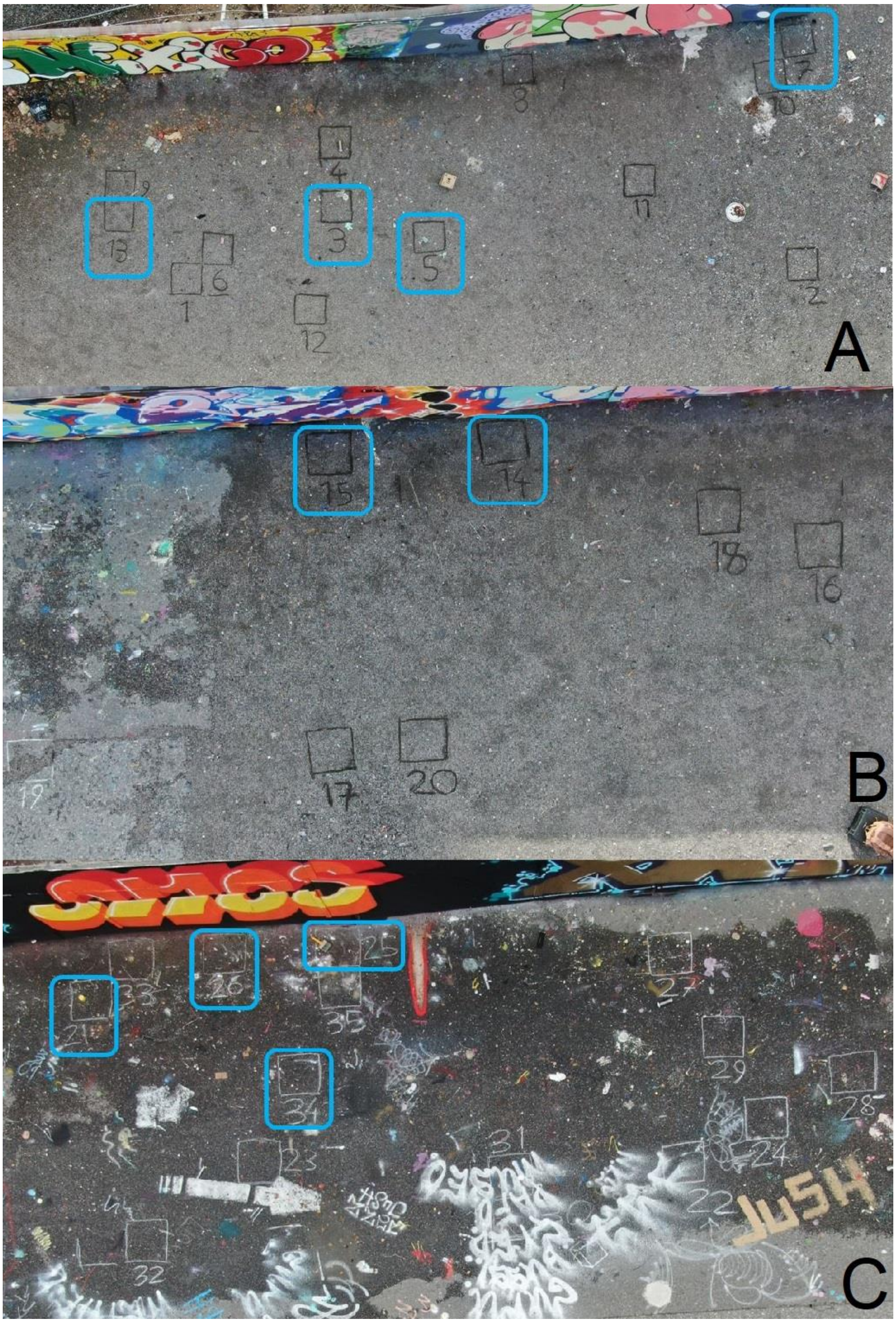

Figure 8. The 10 litter squares of Suvilahti AOI from segments G1 (A), G2 (B), and A1 (C) presented to the control group outlined in blue. Segment identification G refers to gravel background and A to asphalt. Squares number 3, 5, 7, 13, 14, 15, 21, 25, 26, and 34 were handpicked from the three segments in relative proportions to the original dataset and contain various amounts and types of litter.

3.2.6 Data analysis

The litter categories used for both the ground assessments and the assessments from UAV imagery differ from the ones used by previous studies focusing on marine beach litter

(Fallati et al. 2019; Martin et al. 2018). New site-relevant litter categories were adopted according to the location and the surroundings of the study sites as suggested by Hengstmann & Fischer (2020). Relevant litter categories also make litter counting during the assessments easier. The 14 litter categories used for the assessments were bottle cap, cardboard packaging, cigarette filter/bud, metal litter, paper litter, plastic litter, plastic packaging, plastic bag, plastic bottle, aluminum can, glass fragment, polystyrene piece, unidentified, and other. Numerical data collected during the litter assessments was analyzed utilizing IBM SPSS Statistics Version 26.

The results from the GAs were compared to the results of the UAV imagery detection to determine the accuracy of litter detection from UAV imagery. To test for statistical significance, Wilcoxon signed rank tests were conducted for Suvilahti and Viikki as described by Woolson (2008). Conduction of the Wilcoxon signed rank test requires a number of samples to be compared to one another and was therefore feasible for these two AOIs thanks to their segmented natures (squares in Suvilahti and slices in Viikki). In Suvilahti, the test was conducted separately for three datasets both with and without leaves: the 35 randomly assigned squares, the total of 40 squares including the randomly assigned squares and the five larger squares, and the ten squares showed to the control group.

Of the available statistical tests, Wilcoxon signed rank test was deemed most fitting for the purpose, since unlike paired sample T-test, it does not require normally distributed variables. Although the variables were normally distributed in most datasets, in some they were not. The results of the two remaining AOIs with no segmentation to squares or slices during the assessments, Kyläsaari and Toukola, were analyzed by a simple percentage comparison. The imagery detection results were divided by the GA results and multiplied by hundred to get an imagery detection percentage. The same was also done for the results from Viikki and Suvilahti, including the control group. The results of the control group were compared to the corresponding results of the GA and the UAV imagery detection with the Wilcoxon signed rank test. Additionally, the internal consistency of the control group's results was analyzed with a reliability test and the resulting Cronbach's Alpha value as introduced by Cronbach (1951).

To determine in which litter categories the detection was most successful, percentage comparison was also conducted to the litter categories and leaf detection results, comparing imagery detection to the GA. For this comparison, all AOIs and the control group assessment were included.

Orthomosaics were constructed for each AOI using Pix4Dmapper. The software can automatically construct various types of orthomosaics from the imagery captured with Pix4Dcapture. However, they were not used for data analysis due to their lower reliability in displaying every recorded pixel for litter detection and remained more of a curiosity for this study. Instead, litter detection from UAV imagery was carried out from a set of individual photographs for each AOI.

4 Results

4.1 Questionnaire results

Responses were received from the following countries (quantities in brackets): Finland (4), Germany (1), Portugal (1), and Sweden (13) for a total of 19 participants. Response rate of the questionnaire was 3.7%. Of participants, 42% (8) was utilizing a UAV and 58% (11) was not. 75% of users were Swedish and the rest Finnish.

Of the 19 responses, 11 municipalities reported currently not utilizing a UAV within the scope of this questionnaire. On average, 2.4 reasons were given for not utilizing a UAV with an expected value (mode) of three. The most common reasons were *Lack of expertise* and *Lack of knowledge*, both at 55% of the answers, followed by *No need*, and *Legislative issues* (Fig. 9). Other reasons included lack of funding, absence of plans, and need of further information and education on the topic. No one listed the price of UAVs themselves or weather conditions as a reason for not using a UAV.

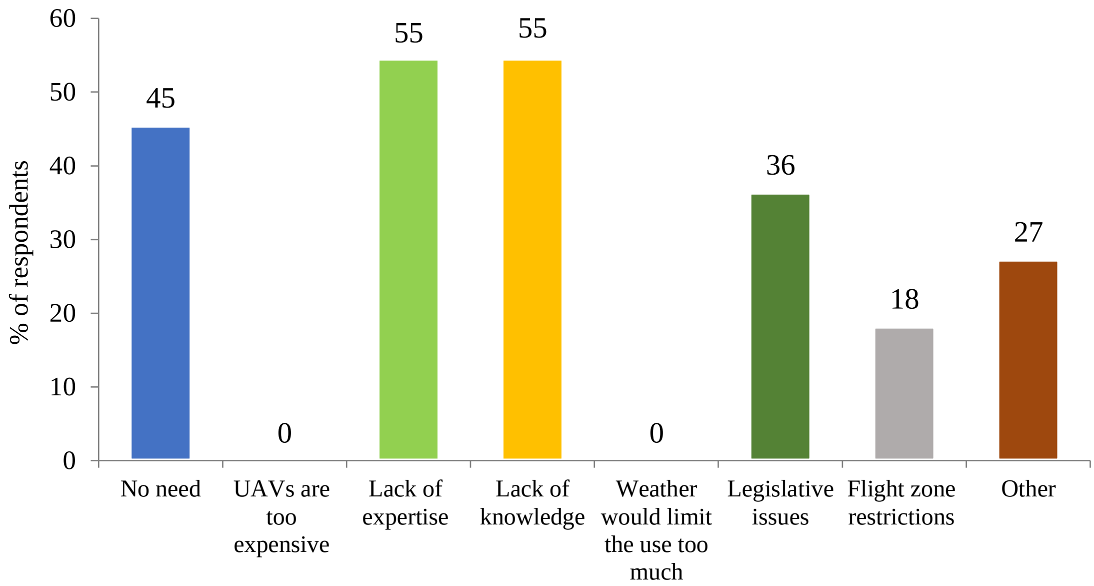

Figure 9. Answers to question 2 for non-users of the questionnaire on UAV utilization: “Why has your municipality not used a UAV for environmental monitoring so far?” Reasons not to use a UAV illustrated as percentages of responses. Eleven municipalities reported not to be using a UAV (n = 11).

The remaining eight municipalities reported to be using a UAV. On average, a municipality had 2.5 applications for UAVs, ranging from one to five with an expected value of two (Fig. 10). The most common frequencies of application use among respondents per category were a few times per year or monthly for *Beach littering*, monthly for

Littering, and once per year for *Traffic monitoring* and *Forest management*. Applications *Agricultural monitoring*, *Animal monitoring* and *Inspection of industrial areas* have been most commonly used less than once per year or a few times per year, and *Inspection of private properties* and *Other* applications have most commonly been used a few times per year. *Other* applications included monitoring of reed clearings on bird wetlands, dumping, beach protection law obedience, and stormwater systems as well as their recipients. Inspection of oil spills at city shores, map updating, and conduction of land surveys were also included in this category.

For evaluating the successfulness of different applications, participants who were currently utilizing a UAV (n = 8) were asked to rate the successfulness of each application they have had experience with on a scale from 1 to 5 (1 = total failure, 2 = goals not reached, 3 = somewhat successful, 4 = success, 5 = success above expectations). The user's successfulness score on average was 4.4, whereas the average successfulness score of different applications was 4.1. The most successful application has been *Inspection of private properties* (score 4.7), followed by *Forest management*, and *Other* applications (Fig. 10). Least success has been in *Beach littering monitoring* and *Animal monitoring* (3.5).

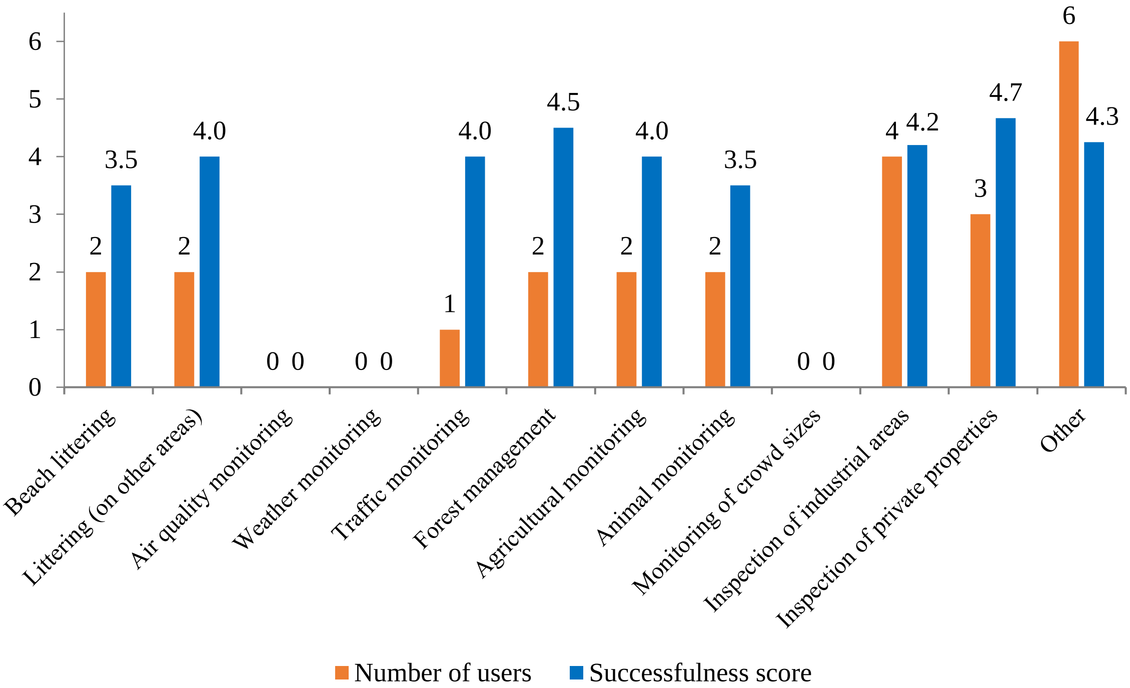

Figure 10. Number of users and the average successfulness score on a scale of 1 to 5 (1 = total failure, 5 = success above expectations) per UAV application, illustrating answers for the questions 3 and 4 of the questionnaire for municipalities and municipal environmental authorities on UAV utilization in environmental monitoring, n = 8.

Among the nine respondents for the question considering reasons for possible mission failures, an average of 1.7 reasons were given. Six respondents reported reasons for failures and three did not. The most common reasons for failures among the respondents were *Weather* at 50% of the respondents, followed by *Poor knowledge of the area of interest* and *Poorly selected goal and/or scope* (Fig. 11). *Other* reasons included image quality and miscommunication between pilots and customers, apparently resulting in missing the point of interest (POI). No one reported *Hardware malfunction, Flight zone restrictions* or *Collision with a bird* as a reason for failure.

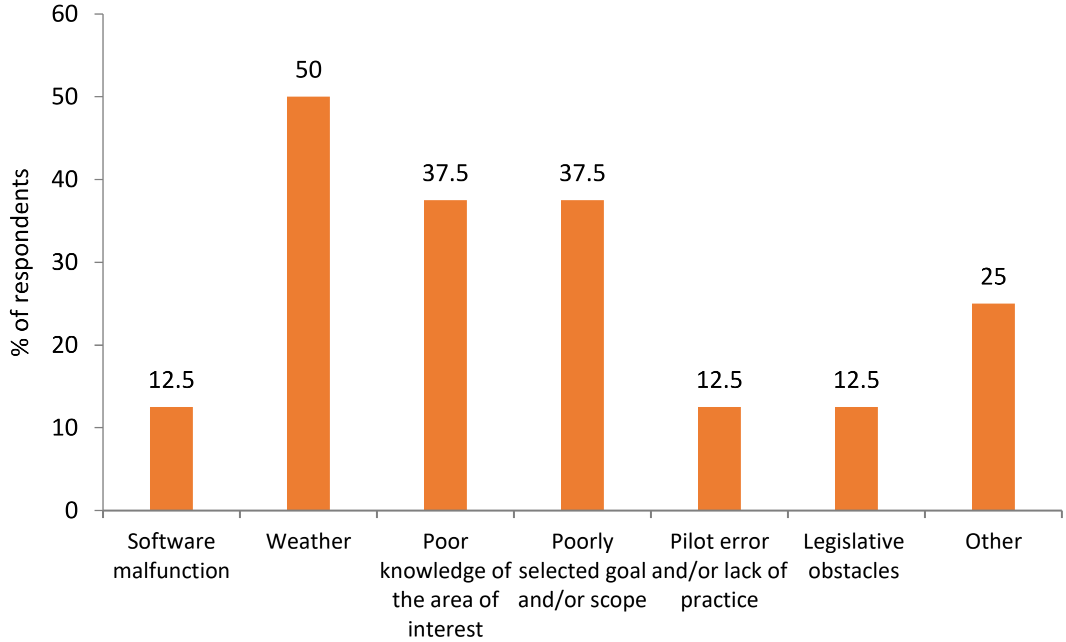

Figure 11. Reported reasons for failures as percentages of respondents from eight active users and one currently non-user but likely former user, n = 9, illustrating answers for question 5 of the questionnaire on municipal UAV utilization in environmental monitoring. Any reason that inhibited a flight mission to produce the intended outcome may be considered as a reasons for a failure.

Future plans of participants were diverse, yet most often involve UAV utilization. Nearly 74% of all participants were willing to purchase a UAV, have concrete plans for acquiring, or have already been using one (Fig. 12). Of the eleven non-users, only four did not have plans for acquiring a UAV for municipal environmental monitoring and inspecting use, whereas six (55%) did. More specifically, participants' plans included 3D model generation with volume calculations, high temporal resolution map updating and construction site monitoring, city planning, environmental accident monitoring, advertisement footage capture, and monitoring of littering and stormwaters. Four participants (21%) did not answer this open question.

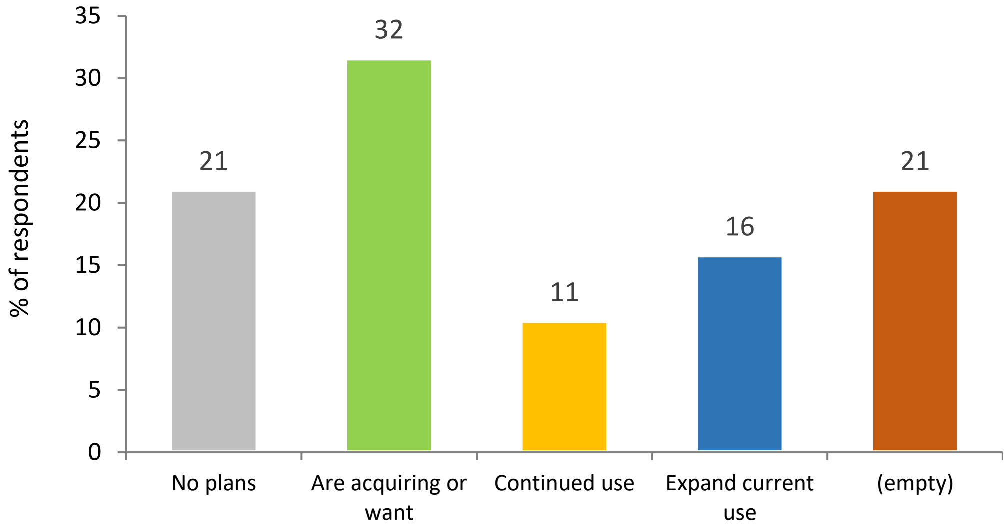

Figure 12. Percentages of respondents according to their UAV utilization plans, n = 19, illustrating answers for question 6 of the questionnaire on municipal UAV utilization in environmental monitoring. Four participants chose not to answer this open question (empty).

4.2 Litter monitoring experiment results

4.2.1 Ground assessment results

Various sizes and types of litter were encountered in the AOIs (Fig. 13). Suvilahti ground assessment for the 1 m × 1 m squares (SGA1) and for 0.5 × 0.5 m squares (SGA2) yielded somewhat differing results due to the varying square allocation methods, randomized versus manually assigned, but were treated as a combined dataset since differences in square allocation methods do not affect the litter detection from UAV imagery. For instance, SGA1 showed a density of 27.2 items/m^2 (litter plus leaves), whereas SGA2 showed a density of 13.6 items/m^2 (Table 2). Combined ground assessment of SGA1 and SGA2 showed densities of 9.8 litter/m^2 and an item density of 18.6 items/m^2 with a total litter count of 135, leaf count of 120, and an area of 13.8 m^2. Although eleven days passed between SGA1 and SGA2, some individual pieces of litter were detected during both assessments in an incident where one square from each assessment overlapped with one another (Fig. 14).

Figure 13. Examples of litter varieties encountered in the areas of interest during the ground assessments of the litter monitoring experiment. A: a syringe partially covered by fallen leaves in Viikki with a pen for scale. B: a metallic bottle cap in Suvilahti. C: a paint roller and an upside-down spray paint bottle cap in Suvilahti. D: a piece of plastic litter in Suvilahti. E: litter in multiple categories partially concealed by vegetation including a black plastic microwave convenience food dish in Kyläsaari.

Table 2.
Sizes of all four areas of interest (AOIs) of the litter monitoring experiment and their litter densities based on ground assessments. SGA1 refers to the Suvilahti ground assessment that covers the 1 m × 1 m squares and SGA2 to the Suvilahti ground assessment that covers the 0.5 m × 0.5 m squares. Item density includes leaves detected within the litter squares in Suvilahti. Since leaves were not accounted for on other AOIs, their litter and item densities are equivalents.

AOI / **Descriptions**	**Suvilahti**			**Kyläsaari**	**Viikki**	**Toukola**
Segment	SGA1	SGA2	Combined			
Surface area (m^2)	5.00	8.75	13.75	62.50	495.00	1830
Litter count	52	83	135	217	35	25
Litter density (litter/m^2)	10.40	9.49	9.82	3.47	0.07	0.01
Leaf count	84	36	120	-	-	-
Item density (items/m^2)	27.20	13.60	18.55	3.47	0.07	0.01

The trapezoid shaped Kyläsaari AOI had a density of 3.5 litter/m^2 with 217 total pieces of litter and an area of 62.5 m^2 (Table 2). In Viikki, strong winds preceding the assessment removed some of the litter in the AOI; hence, the litter density was relatively low, 0.07 litter/m^2. Toukola AOI had the lowest litter density overall with just 0.01 litter/m^2.

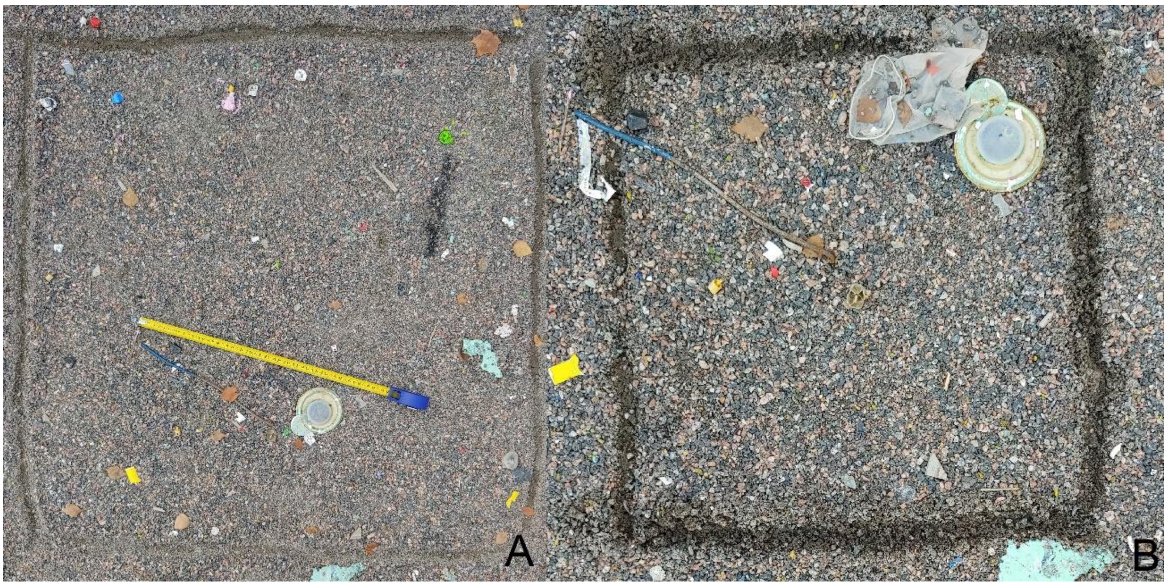

Figure 14. Litter square #1 of the Suvilahti ground assessment (SGA) 1 (A) and litter square #3 of the SGA2 (B) from the litter monitoring experiment containing a few shared pieces of litter, e.g. a lid of a paint container. The size of the square is 1 × 1 meters in image A and 0.5 × 0.5 meters in image B. The square locations were manually assigned for SGA1 and randomized for SGA2, resulting in these two squares overlapping.

4.2.2 UAV imagery detection results

The assessment from UAV imagery in Suvilahti yielded a total of 140 pieces of litter and 83 leaves detected for a total of 223 items as seen on Table 3. Leaves were most abundant category, followed by bottle caps and unidentified litter. Total litter detection rate was 103.7% but the detection rate of leaves was considerably lower, 69.2%. Item detection rate taking both litter and leaves into account was 87.5%.

Table 3.
Detection rates, ground assessment item counts (GA), and UAV imagery detection counts for each area of interest (AOI): Suvilahti, Kyläsaari, Viikki, and Toukola. Suvilahti AOI contains combined square results of all 40 squares. Non-detected litter categories are left blank as are incalculable percentages, i.e. where either of the values is zero. Detection rate is calculated as: (UAV imagery detection count/GA count) × 100.

AOI	Suvilahti			Kyläsaari			Viikki			Toukola		
Results / Category	Detection rate (%)	GA	UAV imagery detection	Detection rate (%)	GA	UAV imagery detection	Detection rate (%)	GA	UAV imagery detection	Detection rate (%)	GA	UAV imagery detection
Aluminum can	-	-	-	33.33	3	1	100.00	1	1	-	-	-
Bottle cap	90.48	63	57	37.50	8	3	-	-	-	200.00	1	2
Cardboard packaging	100.00	3	3	66.67	21	14	150.00	2	3	50.00	2	1
Cigarette filter/bud	255.56	9	23	40.00	5	2	88.89	18	16	84.21	19	16
Glass fragment	-	-	-	40.00	15	6	-	-	-	-	-	-
Metal litter	46.15	13	6	0.00	3	0	-	-	-	-	-	-
Paper Litter	50.00	2	1	100.00	29	29	150.00	2	3	-	-	-
Plastic bag	-	-	-	266.67	3	8	-	-	-	-	-	-
Plastic bottle	-	-	-	60.00	5	3	100.00	1	1	-	-	-
Plastic litter	37.04	27	10	52.63	38	20	75.00	4	3	-	-	-
Plastic packaging	100.00	1	1	97.44	39	38	200.00	1	2	50.00	2	1
Polystyrene piece	-	-	-	16.67	24	4	0.00	1	0	0.00	1	0
Unidentified	-	0	27	-	0	41	-	0	0	-	-	-
Other	70.59	17	12	50.00	24	12	60.00	5	3	-	-	-
Leaves	69.17	120	83	-	-	-	-	-	-	-	-	-
Litter total	103.70	135	140	83.41	217	180	91.43	35	32	80.00	25	20
Items total	87.45	255	223	-	-	-	-	-	-	-	-	-

In Suvilahti, there were clear cases of false positives in the cigarette filter/bud category. The 27 unidentified pieces of litter also contributed to the higher UAV imagery detection count. Together these two categories with likely hidden false positives in other categories raised the litter detection rate past 100%. Altogether there were 41 or 29.3% of all items in Suvilahti that were either false positives, misclassified or unclassified. Plastic, metal, and paper litter were the most difficult to detect from UAV imagery with detection rates of 50% or lower.

Litter detection rate in Kyläsaari, 83.4%, was similar to the item detection rate in Suvilahti. However, the distribution of detection rates varied notably (Table 3). The only clear false positives were in the plastic bag category with five false positives. Additionally, 41 items were unidentified, resulting in 46 (25.4%) of items to be either false positives, misclassified or unclassified. The most accurate detection rates were in categories paper litter, plastic packaging, and cardboard packaging while the worst detection rates were seen in categories metal litter, polystyrene piece, and aluminum can.

Viikki had a detection rate of 91.4%, ignoring leaves. Total detection rate was very high, and some percentages showed up to 200% detection rates. Large percentage variations between categories in Viikki were due to the low number of litter as many categories had less than five individual pieces. Thus, even a single false positive or misclassification may have caused detection rates to increase or decrease dramatically, such as in plastic packaging and paper litter categories.

Toukola had the lowest litter count of all AOIs as only 25 pieces of litter were detected in the ground assessment and 20 in UAV imagery detection (detection rate of 80%). Most litter in the AOI composed of cigarette filters/buds. Similarly to Viikki, detection rates of some categories varied greatly due to a low number of litter.

The asymptotic 2-tailed significance values of the Wilcoxon signed rank test showed no statistically significant difference between the GA and UAV imagery detection results for the 35 0.5 × 0.5 m litter squares in Suvilahti when only litter was considered (Z = -1.361, p = 0.174) nor when also accounting leaves (Z = -0.654, p = 0.513) (Table 4). The addition of the five 1 × 1 m squares did not change this outcome. For all 40 squares, the two assessments were even more alike when only considering litter (Z = -0.730, p = 0.466), while taking leaves into consideration increased the inconsistency between the two assessment results but did not reach statistical significance (Z = -0.534, p = 0.125). In Viikki, the Wilcoxon test results (Z = -0.744, p = 0.457) showed no significant difference between the two datasets.

Table 4.
Descriptive statistics of the datasets and the results of the Wilcoxon signed rank test between the ground assessment (GA) and the UAV imagery detection (UAV) results from Suvilahti and Viikki AOIs of the litter monitoring experiment.

Area of Interest	Objects	GA mean	GA sd.	UAV mean	UAV sd.	Z	p
Suvilahti, 35 squares	Litter	2,37	2,20	2,71	1,91	-1.361	0.174
	Items	3,40	3,47	3,11	2,44	-0.654	0.513
Suvilahti, 40 squares	Litter	3,38	3,93	3,50	3,15	-0.730	0.466
	Items	6,38	8,90	5,58	7,22	-1.534	0.125
Viikki	Litter	3.50	2.27	3.20	2.62	-0.744	0.457

Direct detection rate comparisons between AOIs with high and low litter counts can be problematic since a single piece of litter in an AOI with low litter count can generate notable changes in the detection rate. To give each piece of litter the same influence on the final results, a weighted arithmetic mean over all AOIS was calculated, yielding an item detection rate of 85.7% (Table 5).

Table 5.
Overall combined detection rates of all four areas of interest (AOI) of the litter monitoring experiment with simple arithmetic mean and weighted arithmetic mean with and without taking the leaves in Suvilahti AOI into consideration.

Combined detection rate of all AOIs (%)	Litter total (without leaves)	Items total (with leaves)
Arithmetic mean detection rate	89.64	85.57
Weighted arithmetic mean detection rate	90.53	85.71

4.2.3 Control group results

The control group had a litter detection rate of 67.9% and an item detection rate (including leaves) of 49.0% (Table 6). The control group detected on average 1.06 pieces of litter per square less than actually existed. On the contrary, the UAV imagery detection detected on average one piece of litter more than actually existed (Table 6, Fig.15), making the accuracies of the two nearly as good. Thus, the offset or bias caused by a single assessment conductor is practically non-existent when only considering litter.

Table 6.
Results of the control group. Detection rate and the average number of litter per square detected by the control group (Control), during UAV imagery detection (UAV) and ground assessment (GA), control group's results comparison to ground assessment and UAV imagery detection over the ten squares presented to the control group from Suvilahti area of interest. Comparison is made by subtracting ground assessment results from the other two, resulting in a figure describing how much more or less litter was detected by the control group or during UAV imagery detection compared to the ground assessment. Negative numbers show fewer litter and positive more litter detected per square than actually existed.

		Average per square			**Average difference per square**		
Comparison / Category	Control group' s detection rate (%)	Control group average	UAV	GA	Control - GA	UAV - GA	Control – UAV
Bottle cap	13.33	0.16	1.30	1.20	-1.04	0.10	-1.14
Cardboard pack.	-	0.00	0.00	0.00	0.00	0.00	0.00
Cigarette filter	20.00	0.02	0.90	0.10	-0.08	0.80	-0.88
Screw/nail	4.00	0.02	0.20	0.50	-0.48	-0.30	-0.18
Paper litter	-	0.22	0.00	0.00	0.22	0.00	0.22
Plastic litter	91.43	0.64	0.10	0.70	-0.06	-0.60	0.54
Plastic packaging	-	0.10	0.00	0.00	0.10	0.00	0.10
Unidentified	-	0.94	1.10	0.00	0.94	1.10	-0.16
Other	17.50	0.14	0.70	0.80	-0.66	-0.10	-0.56
Leaves	10.00	0.16	0.40	1.60	-1.44	-1.20	-0.24
Litter total	67.88	2.24	4.30	3.30	-1.06	1.00	-2.06
Items total	48.98	2.40	4.70	4.90	-2.50	-0.20	-2.30

Both the UAV imagery detection and the control group found less leaves than actually existed, but the failures of spotting leaves corrected some occurrences of false positives for the UAV imagery detection, while for the control group the missed leaves amplified the number of missed items even further (Table 6). The control group detected on average 2.5 items less than actually existed, which decreased their overall accuracy. Thus, the magnitude of offset was noticeable with a detection difference of 2.3 items in favor of the UAV imagery detection when leaves were accounted for.

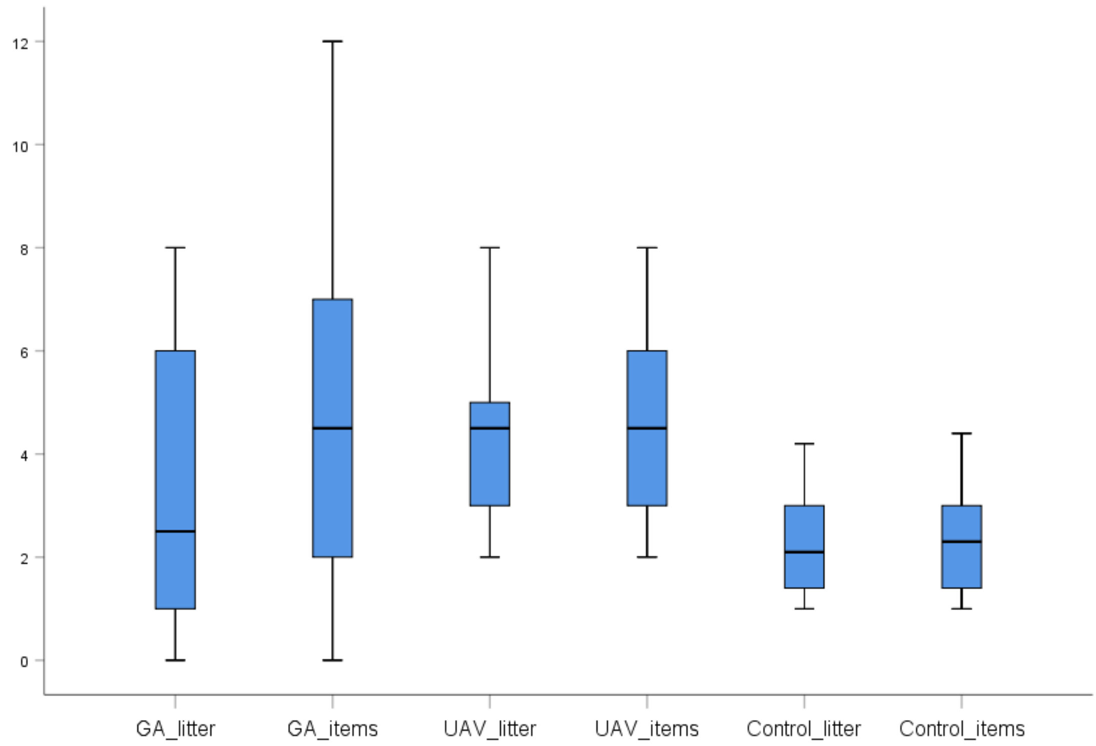

Figure 15. Litter and item detection results of the ground assessment (GA), the UAV imagery detection (UAV) and the control group (Control) for the 10 squares from Suvilahti area of interest presented to the control group. The lower boundaries of the blue rectangles represent the first quartiles and the upper boundaries the third quartiles of each dataset. The black horizontal lines represent the medians, and the whiskers the minimums and the maximums of each dataset. Vertical axis indicates the number detected objects.

The control group detected less litter but misidentified objects as plastic and paper litter. They seem to have considered the smallest pieces of litter such as bottle caps as background variation. Categories in which the control group outperformed the UAV imagery detection are Cigarette filters/buds and Plastic litter.

Internal consistency of the control group's results was relatively high or at least acceptable with a Cronbach's Alpha values of 0.776 and 0.805 when excluding and including leaves, respectively (Table 7). According to the Wilcoxon test (Z = -1.074, p = 0.283), no statistically significant difference existed between the GA and the average results of the control group when excluding leaves. However, when leaves were included, the two datasets differed with statistical significance (Z = -2.193, p = 0.028). Incidentally, comparisons of the UAV imagery detection and control group's results for both litter and items yielded the same outcomes from the Wilcoxon signed rank test despite of the differences in the datasets. This was due to low number of sample squares and the rank allocation method of the Wilcoxon test.

Table 7.
Descriptive statistics of the datasets, the results of the Wilcoxon signed rank test between various datasets, and the results of the reliability test from Suvilahti area of interest for the 10 squares presented to the control group. GA stands for ground assessment, UAV for UAV imagery detection, Control for control group and sd. for standard deviation. The reliability test was conducted to test the internal consistency of the control group's answers.

Objects	**Litter**	**Items**	**Litter**	**Items**	**Litter**	**Items**
GA mean	3.30	4.90				
GA sd.	2.75	3.73				
Control mean	2.24	2.40				
Control sd.	0.97	1.03				
UAV mean	4.30	4.70				
UAV sd.	1.89	2.06				
Comparison	GA - UAV	GA - UAV	GA - Control	GA - Control	UAV - Control	UAV - Control
Z	-1.338	-0.154	-1.074	-2.193	-2.668	-2.668
p	0.181	0.877	0.283	0.028	0.008	0.008
Cronbach's alpha			0.776	0.805		

5 Discussion

5.1 Questionnaire

The projections done by both De Miguel Molina & Segarra Oña (2017) and Traficom (2020a) suggest that UAVs should have already found their ways into many organizations throughout society, which created high expectations for the number of responses in the questionnaire. Despite this expectation, response rate in the questionnaire was low even though reminder emails were sent.

A few possible explanations for the low answering rate can be suggested. Brüggen et al. (2011) reported that respondents do not often see incentives as important motives for participating in online surveys, and that the greatest motivations are intrinsic and based on e.g. enjoyment, interest, and willingness to comment. Furthermore, participants motivated by intrinsic reasons can be expected to make up a bulk of all respondents, whereas respondents motivated by incentives can be expected to be in the minority. If enjoyment and interest are often main drivers for participation, then voluntary surveys might not exceed the participation threshold for some recipients or make participation high on their priority lists, although the topic would be relevant to their work. Likewise, according to the questionnaire results, many participants were not well-informed of UAVs since they are relatively novel tools and, and thus many recipients may not have much to comment on the topic. Although the results of the questionnaire were offered as an incentive in a form of a report to the participants, this most likely did not draw in many additional respondents.

Additionally, the recipients might be experiencing "questionnaire fatigue" in particular due to current remote work conditions. Moreover, recipients might be deterred from answering, if the recipient's municipality is not using a UAV or the recipient is unaware of its utilization within the municipality. This theory is in line with the results of Brüggen et al. (2011): if the respondent has little to no intrinsic motivations, they will most likely not participate in a voluntary questionnaire.

The reasons for not using a UAV are mostly related to information. There is not enough knowledge, expertise, or insight of UAVs and their possibilities among municipalities' environmental authorities. Some municipalities who listed these reasons might benefit from the use of a UAV but might not be aware of said benefits. An information deficit is hardly surprising since affordable, commercially available UAVs are relatively novel tools available for municipal use.

Legislative issues have also deterred UAV acquisition and EU-member countries have had varying legislation considering the use of UAVs. However, the EU commission regulation 2019/947 is aimed to unify the legislation from January 2021 onwards (EUC 2019). More universal legislation will make application sharing and implementing even easier in the future. A brief summary of the legislative field considering UAV utilization in Finland is given in Appendix 1.

Used UAV applications were more related to “creative” solutions, such as inspections and other presumably free-flying missions where the pilot has control of the UAV and its sensors, than to “conventional” UAV and aerial imagery solutions. “Conventional” applications, such as forest and land surveys, typically use automated flights with preplanned flight parameters similarly to the litter monitoring experiment and are nadir-oriented, i.e. the sensor is oriented towards Earth’s center. This hints that among municipalities UAVs are used more as an extension of photo documenting methods utilized during ground assessments, such as smartphones and cameras, rather than treated as nadir-oriented extension of aerial and satellite imagery.

Nonetheless, the application pool of UAVs in environmental monitoring is quite vast. In preceding literature, e.g. monitoring of pavement surfaces (Garilli et al. 2021) and landfills (Baiocchi et al. 2019; Gasperini et al. 2014; Hernina et al. 2020; Nikulishyn et al. 2020; Savchyn & Lozynskyi 2019) may been seen as more “creative” applications, whereas monitoring of landslides (Godone et al. 2020; Sestras et al. 2021) and greenbelts (Duan et al. 2019) are closer to “conventional” applications. Although forest, agricultural, and land survey applications were present in the questionnaire results, even more municipalities use UAVs for inspections of industrial areas and private properties. Such applications depend on great maneuverability and capability of inspecting details from various angles, both of which have been reported as features of UAVs in other applications (Howard et al. 2017; Van Tilburg 2017; Weldon & Hupy 2020).

Use of UAVs for inspections and other similar applications seems logical considering the spatial resolution of a UAV based on the results of the litter monitoring experiment. The necessary spatial resolution for conducting an inspection on an industrial site where inspection of details may be crucial is much higher that the spatial resolution required for conducting e.g. a forest survey. However, the division of applications between the categories “creative” and “conventional” is not well defined. Reported applications such as e.g. monitoring of bird wetlands, stormwaters, and oil spills, may utilize varied methodological approaches.

Overall, these results may be considered rather surprising, since most available literature on UAV utilization in environmental monitoring is focused on nadir-oriented solutions (Andriolo et al. 2020; Bao et al. 2018; Duan et al. 2019; Fallati et al. 2019; Hengstmann & Fischer 2020; Martin et al. 2018; Merlino et al. 2020). This demonstrates the need for flexibility and versatility in a tool used for municipal environmental monitoring and inspecting. Another reason for the uneven distribution of applications among participants is simply the fact that forest surveys etc. can also be carried out by other airborne solutions or satellite imagery with pre-existing methods.

Division between presumably nadir-oriented or conventional and more creative utilization cannot be detected in mission success rates. Presumably nadir-oriented missions were not any more successful than the more creative solutions, although *Inspection of private properties* was the most successful application overall. There is slight variation, but with the given sample size, noteworthy calculations are impossible. Interestingly, *Beach littering* was on the shared last place in successfulness among the participants and was slightly outperformed even by *Littering (on other areas),* although more knowledge and examples of beach litter monitoring can be obtained from previous literature (Andriolo et al. 2020; Bao et al. 2018; Fallati et al. 2019; Hengstmann & Fischer 2020; Martin et al. 2018; Merlino et al. 2020). However, since the combined successfulness score average of the participants is over four the utilization of UAVs can be considered very successful.

Weather was the most common reason for failures. It was followed by the same problems deterring the use of UAVs in the first place: lack of information. Poor knowledge of AOIs, POIs, and incorrectly setting the goal and scope of missions also caused failures among the users. Therefore, it can be concluded, that careful mission planning is key to success, weather permitting.

Answers of one participant were singled out in questions 4 and 5. According to their answers, they are currently not using a UAV but still answered these two questions intended for UAV users. They were excluded from the analysis of success rates (question 4) because their reported utilization category was *Do not know (empty answer)* without any further details. However, the participant was included in the analysis of reasons for failures (question 5), since among other reasons they reported *Pilot error and/or lack of* *practice* as a reason for failure. The participant was interpreted to have had firsthand experience with UAVs in the past but having later discontinued the use.

Future plans of most participant municipalities include UAV utilization within the scope of this questionnaire. Most of current users are planning to adopt new applications. As a relatively novel tool, non-users currently outnumber users among participants, but the situation is likely to change in a few years according to the questionnaire results as well as other projections (De Miguel Molina & Segarra Oña 2017; Traficom 2020a).

Many if not all of the applications mentioned in the results of the questionnaire are also applicable for BVLOS (beyond visual line-of-sight) flight missions. During these missions the visual contact between the UAV and its pilot is broken, inflicting various additional risks but also allowing assessment conduction of AOIs farther away and behind visual obstacles. Requirements for a BVLOS flight are described in Appendix 1. Should BVLOS missions gain popularity, time-efficiency of assessments and inspections conducted with a UAV would improve greatly, since authorities' physical visits to AOIs merely to maintain VLOS to the UAV would no longer be necessary.

5.2 Litter monitoring experiment

The total item detection rate from UAV imagery compared to ground assessment was 85.7%, which is comparable to (Fallati et al. 2019; Merlino et al. 2020; Hengstmann & Fischer 2020) and even higher than (Martin et al. 2018) results in previous literature using similar methods. UAVs have been found comparably accurate to conventional methods including LIDAR also in landfill characteristics studies (Baiocchi et al. 2019; Gasperini et al. 2014). The detection rate result was obtained when both the GA and the UAV imagery assessments were carried out by a single individual and the bias or offset was intentionally mitigated by a two-week waiting period between the two assessments.

The manual square allocation during SGA1 was done to ensure a sufficient amount of litter would be subjected to (possible) detection from UAV imagery should the randomized squares during SGA2 fall on spots containing no or only little litter. Consequently, SGA1 yielded higher item densities.

Leaves had a low detection rate compared to litter in Suvilahti. Most leaves present were relatively small birch leaves and similarly colored as the background with brown being the dominant color. Brightly colored, distinctively shaped, and larger leaves, such as maple leaves, would have most likely had a drastically higher detection rate.

Plastic, paper, and metal litter proved to be the litter categories most difficult to detect from UAV imagery. Reasons for this in case of Suvilahti might be the abundance of paint splashes on the foreground of the graffiti fence on both gravel and paved surfaces. It is possible, that some individual pieces of litter were either subconsciously or by mistake dismissed as paint splashes rather than identified as litter. Unclear, pixelated, and typically white in color smears on the ground were challenging to identify correctly.

Metal litter consisted mainly of screws, nails, and other similarly shaped objects, which are challenging to spot from a pixelated image. Difficulty to detect and identify small objects from pixelated images is not surprising. Hengtsmann & Fischer (2020) have reported that the detection rate of objects 25 cm^2 in size fall from 80% to 31% when the altitude doubles from 10 meters to 20 meters. Similar effect happens when identifying objects while the altitude remains constant: the smaller the object, the more pixelated it appears and separating it from the background becomes increasingly difficult.

According to the results, practice and experience with UAV image interpretation has an effect on how well different objects can be detected. This would explain, why the control group had lower detection rates compared to UAV imagery detection rates, which slightly improved over time, and why the item detection results of the control group and the GA differed with statistical significance, whilst the results of the UAV imagery detection did not. Then again, the UAV imagery assessment resulted in numerous false positives compared to the control group in multiple categories possibly due to overconfidence. The combined average litter detection results (excluding leaves) per square for the UAV imagery detection and the control group was 3.27 compared to the GAs 3.30, which indicates that while neither the UAV imagery detection nor the control group was better than the other in litter detection accuracy (4.3 and 2.2, respectively), their average result seems to give the most accurate results.

Leaf detection rate of the control group was very low possibly due to lack of practice and fear of false positives. The effect of visiting the area and conducting the ground assessment prior to UAV imagery screening versus not doing so might also have an impact on the two results. However, the control group was well aware of the existence of leaves in the AOI, since they were provided overall descriptions and photographs of the area, a couple of litter squares containing leaves were assessed together for practice, and they were also tasked to count the leaves as their own category. Yet, they mostly failed to identify them. If leaves or other objects that are challenging to spot from the background are to be identified from UAV imagery, practice seems to improve the results.

For instance, Kyläsaari litter detection rate (excluding leaves) is comparable to Suvilahti item detection rate (including leaves). The reason for similar detection rates might be due to increased proficiency of the assessment conductor in item detection from UAV imagery, since Kyläsaari was the last the AOI to be assessed.

Litter was abundantly present in Kyläsaari in various sizes and materials. The AOI was not segmented for the GA or the UAV flight, and neither was Toukola AOI. Segmentation of areas of interest prior to assessment conduction could be recommended for future studies since segmentation makes the assessment conduction easier and enables the use of statistical tools for analyzing the results.

The reasons for Suvilahti and Kyläsaari having such large variation between detection rates in some categories, such as Bottle caps and Cigarette filters/buds, are open for speculation. Most obvious explanations could be the different background materials. Another explanation could be the differences in litter varieties within a category. Most bottle caps in Suvilahti were spray paint cans with a more distinctive shape, whereas Kyläsaari contained mainly caps from drinking bottles. Although larger than spray paint bottle caps, these caps might be mistaken as pebbles, unless placed horizontally, revealing the circular shape. Kyläsaari had stones and rocks of varying sizes from sand to boulders and heavy vegetation cover on parts of the AOI, which did not only directly conceal some of the surface area of pieces of litter but also casted a web of shadows on the AOI, making visual litter detection from UAV imagery ever more challenging. The vegetation itself might also be misinterpreted as litter in some cases, or vice versa, increasing inaccuracy in categories containing smaller litter, such as paper litter, plastic litter, and especially polystyrene pieces.

Low litter amount in Viikki is thought to be partly due to stormy days preceding the ground assessment and the UAV flight. The area was visually confirmed to have an abundance of litter a few days earlier, but strong southerly winds of up to 15–18 m/s prevented the utilization of the quadcopter at the time. The larger average size of the pieces of litter in the AOI most likely contributed to the comparably high detection rate of over 91% with only few false positives. This is supported by the results of both Martin et al. (2018) and Merlino et al. (2020), who reported litter detection reliability to increase significantly for large objects compared to small ones.

Although flight missions in other AOIs used an overlap of 80%, an increased overlapping of 90% was tested for Viikki AOI. However, many of the images taken during the 90% overlap flight turned out blurry due to an unknown reason, overall an unprecedented occurrence. The blurry images captured during the 90% image overlap flight mission might have been caused by rapidly alternating windspeeds and relatively strong winds of ca. 10 m/s with over 16 m/s gusts. The conditions were demanding considering the quadcopter's max wind speed resistance of ca. 8–10.5 m/s according to the manufacturer. Why these conditions affected this mission so heavily while the 80% image overlap flight mission experienced little to no image blurriness, although they were conducted back to back, is unknown. Weather was also found to be the most common reasons for flight mission failures. Whether the restricting weather conditions have been low temperature, high wind speed, rain (all of which may render a UAV useless), or some other factor, is unknown on the basis of the questionnaire results. Nonetheless, the required images of Viikki AOI were acquired and the flight mission completed safely despite of the wind conditions. Considering the continuous necessity of environmental monitoring even in suboptimal weather conditions, this observation is encouraging, since it suggests that UAVs are capable of operating outside of their comfort zones. Yet, low wind speeds are often required for more accurate assessments and measurements (Von Bueren et al. 2015).

Toukola AOI was the first AOI to be assessed and was beforehand thought to contain higher amounts of litter due to the high number of visitors it receives. Ultimately, the litter density on Toukola AOI was the lowest overall. This is partially due to the fact that seawater covered roughly half of the ca. 1830 m^2 assessed and no litter was detected on the surface. Low litter count may also be due to good sanitation services or visitors' willingness to keep the park clean.

Various causes for inaccuracies were discovered. The two-week waiting period between the ground assessments and the assessment from UAV imagery might not have been sufficiently long for all details of the AOIs to fade from the memory of the assessment conductor. This in turn might have improved the detection results. Although problematic for the experiment, in municipal environmental monitoring the increased accuracy achieved by conducting the two assessments back to back is most desirable.

The quadcopter measures the altitude in relation to the takeoff point, which causes spatial resolution variation on flight missions with changing topography. The quadcopter's altitude accuracy is not absolute either and even on flat ground can cause variation of ca. ± 0.2 meters in flight altitude, thereby slightly affecting the GSD. Additionally, all footage was captured with the automated camera settings. This was hoped to result in best image quality for each individual shot while simultaneously mitigating possible errors by the user. However, automated settings change depending on the lighting conditions, which in turn might create variation between images.

Another problem was discovered while planning the flight missions with Pix4Dcapture. The background map, despite of having an option of satellite imagery, did not always correspond perfectly to the actual surroundings. This was evident especially in Suvilahti, where the temporary graffiti fence was not visible on the map and the flight mission had to be planned carefully in order to avoid the airspace of the neighboring construction site which had prohibited photography. Aligning the flight plan perfectly to the surroundings required a few attempts. The correspondence issue was also noted in Toukola, where larger areas of water than intended were recorded due to the shift of the shoreline between the map and reality.

Carrying out a mission with a continuous velocity is somewhat less time-consuming compared to stop and go mode but might increase blurriness of images. However, in bright daylight while flying on low altitudes the difference could be considered negligible but is certainly something to consider while planning a flight mission especially in windy conditions. In hindsight, the flight time of the used quadcopter was not a limiting factor in any of the AOIs. Hence, stop and go mode as trialed by Merlino et al. (2020) could be recommended for the future experiments.

Although Martin et al. (2018) found a UAV to be able to monitor their study site much faster than ground assessment could, the assessment of UAV imagery can be time-consuming should the smallest details to be detected from a large area, like during the litter monitoring experiment. In municipal environmental authority work, however, the absolute number of pieces of litter hardly matters but rather the ability to create documentation of an AOI and report on the issue. During inspections, some POIs are likely to be predetermined, thus mitigating the need for assessing every pixel of the captured images. Therefore, assessing areas with a UAV can be faster than with a GA.

UAVs do also have their restrictions and limitations apart from weather conditions. Their assessment and inspection possibilities are limited by obstacles in the airspace, such as trees and powerlines, which might restrict the utilization of a UAV in an AOI. Obstacle avoidance takes time and they might limit the minimum flight altitude, increasing the GSD and thus decreasing the assessment accuracy. Abundant obstacles also make maintaining VLOS more difficult and may ultimately increase the chance of collision. Obstacles may also prohibit nadir-oriented applications, since the entire AOI may not be recorded due to required evasive maneuvers. UAV utilization might also not be relevant for very large AOIs, as reported by Manfreda et al. (2018) and Matese et al. (2015). Privacy issues may also prove problematic as presented in Appendix 1.

These limitations may be combated with a variety of precautions. As evident from the questionnaire results, insight of the AOI and missions planning are critical for mission success. AOIs with obstacles may be assessed with free-flying missions, allowing nimbler obstacle avoidance and more effective camera orientation to the POIs. Spotter or a co-pilot may be utilized to maintain the VLOS to the UAV and help with obstacle avoidance.

5.3 Call for new research

New surveys with larger recipient pools would be beneficial in the EU, as UAVs are likely to grow in popularity in municipal environmental monitoring and sharing of applications has become easier thanks to universal legislation. More detailed questionnaires surveying reasons of both successfulness and failures are seen as beneficial. It would be beneficial in subsequent studies that use manual detection methods from UAV imagery to have several individuals carrying out both ground assessments and UAV imagery detections individually to make conclusive observations of the role of practice and differences between individuals. Similarly, the size of the control group could be increased. Experiments focusing on the effects of various background surfaces would be beneficial. Comparison studies of time-efficiency between UAV and ground assessment in various tasks would allow more efficient resource allocation for municipalities and their employees. Various automated methods could be implemented and tested for different backgrounds and their time-efficiency and item detection accuracy from UAV images compared to manually conducted visual observations. UAVs should be tested for a range of varying applications that may be beneficial for municipal environmental monitoring. Additionally, practicality of BVLOS flight missions, their effectiveness for different applications, and their time-efficiency compared to VLOS flights should be investigated.

6 Conclusions

The objective of this study was to assess the applicability of UAVs as monitoring tools for municipal environmental monitoring. A simple answer to the research question considering the questionnaire is that the utilization of UAVs has been very successful, and the application pool of UAVs is extensive. According to the questionnaire results, UAVs have been used for a variety of applications for environmental monitoring purposes, both for conventional and more creative ones, of which the latter are more numerous. Reasons for failures have been due to unfavorable weather conditions and lack of UAS knowhow. Importance of up-to-date information and careful mission planning should not be overlooked. UAV users seem to be very pleased with their tool, and ever more municipalities are looking into acquiring one in the future. In the light of the questionnaire results and the response rate, most Finnish, Swedish, and other European municipalities have not yet utilized UAVs for environmental monitoring.

The assessment accuracy of UAVs is concluded to be comparable to that of ground assessments in both spatial and temporal resolutions. The spatial resolution of UAVs is sufficient for spotting and assessing even relatively small details in AOIs with varying background materials and vegetation cover. Manual post-processing of UAV imagery offers a viable alternative for automated methods and practice improves the detection results. The greatest challenges in UAV utilization are weather conditions and limitations set by the AOI.

According to the results, UAVs provide a versatile selection of environmental monitoring applications for the municipal authorities to choose from to help them in their assignments. Learning the necessary skills in order to utilize the quadcopter used in this study takes little time especially when manual screening of images is chosen as the post-processing method. Therefore, UAVs seem easy enough adopt as a part of any municipal environmental official’s toolkit. Additionally, the quadcopter utilized in this study showed noteworthy resilience in challenging weather conditions.

Together these results and observations demonstrate that UAVs are sufficiently accurate and their application pool versatile enough for them to be considered as applicable tools for municipal environmental monitoring. Continued application development and more detailed research on municipal UAV utilization in environmental monitoring is encouraged.

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Appendices

APPENDIX 1

Legislative framework in Finland for UAV utilization in environmental monitoring

Utilization of UAVs is regulated by law in Finland. The government organization Trafi gave a commandment OPS M1-32 in 2018, outlining the rules of UAV utilization (Trafi 2018). The regulation 2019/947 of the European Commission was designed to unify legislation considering UAV utilization in EU member states and came into effect from 2021 onwards (EUC 2019; EUC 2020). While utilizing a UAV for what is considered work, the Finnish Aviation Act also applies unless stated otherwise in the regulation 2019/947 (Aviation Act 2014/864).

Legislation or regulations that guide municipal environmental authorities in their assignment apply regardless of the monitoring method. According to a lawyer of the Association of Finnish Municipalities, M. Nurmikolu (personal communication 16.11.2020), for instance the difference between an observational visit at the site versus a formal inspection remains the same whether they are carried out by traditional methods or not. Therefore, the same legal obligations, guidelines, restrictions, and practices that apply for ground assessment conduction also apply for UAV utilization. For instance, the litigants have a right to be present during a formal inspection, unless this jeopardizes the aim of the inspection (Administrative Procedure Act 2003/434 § 39). Domestic privacy, as defined in HE 2013/214 § 172, is to be preserved while utilizing a UAV the same way as during ground assessments. However, it is possible to commit invasion of domestic privacy, a criminal act, unintentionally while utilizing a UAV. Mere observation of spaces belonging to domestic privacy with a technological device is forbidden, even if no pictures were to be taken (Traficom 2019a; Criminal Code of Finland 2000/531). Theoretically, a formal inspection could be carried out remotely as a BVLOS (beyond visual line-of-sight) flight utilizing a UAV but only if the legal protection of the litigants is considered alongside with the special preparations, permits, and fees of an BVLOS flight, including e.g. airspace reservations (Traficom 2019b).

Some flight parameters are also regulated. With the new regulation, the maximum flight altitude for a UAV without a special permit is 120 meters above sea or ground level and their takeoff weights are limited (EUC 2019). Airports, airspace over some governmental buildings, and areas reserved for the Finnish Defense Forces are restricted flight zones and the maximum flight altitude may be reduced in their proximity (Government degree 2014/930). Additionally, UAV flights over crowds are forbidden and UAVs are to yield all other aviation traffic (Traficom 2020b).

APPENDIX 2

The questionnaire form on municipal UAV utilization sent on October 5th, 2020 to environmental authorities of 149 Finnish municipalities, all 290 Swedish municipalities, and Eurocities WG Waste group with 82 member municipalities (n = 512). The questionnaire was constructed using the E-form platform (E-lomake in Finnish) of the University of Helsinki provided by Eduix Oy.

UAVs in environmental monitoring in urban areas

This questionnaire is launched by the Urban Environment Division of City of Helsinki.

The goal of this questionnaire is to collect user experiences of UAVs as tools for environmental monitoring in urban areas. Here the term "UAV" stands for Unmanned Aerial Vehicle. It covers all variations, such as quadcopters, octocopters, and fixed-wing platforms. The phrase "environmental monitoring in urban areas" covers most activities carried out by the municipal environmental authority that have to do with documenting the state of the environment (for example wellness of vegetation) or phenomena occurring in the environment, such as littering, traffic volumes, stomping patterns in public parks, industrial activities, etc.

Answering will take approximately 5-10 minutes.

The results of the questionnaire will be presented in a publication from the City of Helsinki and in a related master's thesis. They will also be directly shared with the participants.

Should you have any questions considering the questionnaire, please contact Eero Lahtela, environmental intern, tel. +358 40 578 4177, eero.lahtela@hel.fi.

Thank you for participating!

Question 1

Country *

City or municipality *

I accept that my personal information is gathered by answering this survey.

	Yes	No
* Do you accept?	○	○

If "yes" and you would like, please leave us an email address to which we can directly share the results once ready!

Question 2

Are UAVs used for environmental monitoring purposes in you municipality by the municipal authorities?

- ☐ Yes
- ☐ No

If "Yes", proceed straight to Question 3.

If "No", please answer the rest of Question 2. Then proceed straight to Question 6.

Why has your municipality not used an UAV for environmental monitoring so far?

- ☐ There has been no need
- ☐ UAVs are too expensive
- ☐ Lack of expertise
- ☐ Lack of knowledge
- ☐ Weather would limit the use too much
- ☐ Legislative issues
- ☐ Flight zone restrictions
- ☐ Other, what?

Please specify here:

Question 3

On average, how often is an UAV used for the following purposes?

Beach littering

- ☐ Never
- ☐ Less than once per year
- ☐ Once per year
- ☐ A few times per year
- ☐ Monthly
- ☐ Weekly or more often
- ☐ Do not know (empty answer)

Littering (on other areas)

- ☐ Never
- ☐ Less than once per year
- ☐ Once per year
- ☐ A few times per year
- ☐ Monthly
- ☐ Weekly or more often
- ☐ Do not know (empty answer)

Air quality monitoring

- ☐ Never
- ☐ Less than once per year
- ☐ Once per year
- ☐ A few times per year
- ☐ Monthly
- ☐ Weekly or more often
- ☐ Do not know (empty answer)

Weather monitoring

- ☐ Never
- ☐ Less than once per year
- ☐ Once per year
- ☐ A few times per year
- ☐ Monthly
- ☐ Weekly or more often
- ☐ Do not know (empty answer)

Traffic monitoring

- ☐ Never
- ☐ Less than once per year
- ☐ Once per year
- ☐ A few times per year
- ☐ Monthly
- ☐ Weekly or more often
- ☐ Do not know (empty answer)

Forest management

- ☐ Never
- ☐ Less than once per year
- ☐ Once per year
- ☐ A few times per year
- ☐ Monthly
- ☐ Weekly or more often
- ☐ Do not know (empty answer)

Agricultural monitoring

- ☐ Never
- ☐ Less than once per year
- ☐ Once per year
- ☐ A few times per year
- ☐ Monthly
- ☐ Weekly or more often
- ☐ Do not know (empty answer)

Animal monitoring

- ☐ Never
- ☐ Less than once per year
- ☐ Once per year
- ☐ A few times per year
- ☐ Monthly
- ☐ Weekly or more often
- ☐ Do not know (empty answer)

Monitoring of crowd sizes (for instance during events)

- ☐ Never
- ☐ Less than once per year
- ☐ Once per year
- ☐ A few times per year
- ☐ Monthly
- ☐ Weekly or more often
- ☐ Do not know (empty answer)

Inspection of industrial areas

- ☐ Never
- ☐ Less than once per year
- ☐ Once per year
- ☐ A few times per year
- ☐ Monthly
- ☐ Weekly or more often
- ☐ Do not know (empty answer)

Inspection of private properties

- [ ] Never
- [ ] Less than once per year
- [ ] Once per year
- [ ] A few times per year
- [ ] Monthly
- [ ] Weekly or more often
- [ ] Do not know (empty answer)

Other, what?

- [ ] Never
- [ ] Less than once per year
- [ ] Once per year
- [ ] A few times per year
- [ ] Monthly
- [ ] Weekly or more often
- [ ] Do not know (empty answer)

Please specify here:

Question 4

On average, how successful has the use of an UAV been? Please DO NOT answer to categories you previously answered "Never" or "Do not know (empty answer)".

Use the scale from 1 to 5 (1=total failure, 2=goals not reached, 3=somewhat successful 4=success, 5=success above expectations)

	1	2	3	4	5
Beach littering	○	○	○	○	○
Littering (on other areas)	○	○	○	○	○
Air quality monitoring	○	○	○	○	○
Weather monitoring	○	○	○	○	○
Traffic monitoring	○	○	○	○	○
Forest management	○	○	○	○	○
Agricultural monitoring	○	○	○	○	○
Animal monitoring	○	○	○	○	○
Monitoring of crowd sizes (for instance during events)	○	○	○	○	○
Inspection of industrial areas	○	○	○	○	○

	1 2 3 4 5
Inspection of private properties	○ ○ ○ ○ ○
Other	○ ○ ○ ○ ○

Question 5

What have been the reasons for failures, if any?

- ☐ Hardware malfunction
- ☐ Software malfunction
- ☐ Flight zone restrictions
- ☐ Weather
- ☐ Poor knowledge of the area of interest
- ☐ Poorly selected goal and/or scope
- ☐ Pilot error and/or lack of practice
- ☐ Collision with a bird
- ☐ Legislative obstacles
- ☐ Other, what?

Please specify here:

Question 6

What plans does your municipality have for future UAV utilization?

Please send your answers to us by clicking "Submit"!

We expect to get back to you with the results in the spring 2021.

Thank you for your time!

Proceed

APPENDIX 3

Weather characteristics during the UAV flights in 10-minute intervals. Data is provided by the Finnish Meteorological Institute and obtained through their Download observations service (FMI 2021). Several flight mission alignment attempts with the Pix4Dcapture flight planning tool were required on some AOIs (Suvilahti 2, Kyläsaari, Viikki) and on Viikki AOI more than one flight mission was conducted. All UAV flights were conducted within the reported time frames.

AOI	Year	Month	Day	Time	Cloud amount (1/8)	Pressure (msl) (hPa)	Relative humidity (%)	Precipitation intensity (mm/h)	Air temperature (°C)	Dew-point temperature (°C)	Horizontal visibility (m)	Wind direction (deg)	Gust speed (m/s)	Wind speed (m/s)
Toukola	2020	9	14	16:10	1	1016.3	79	0	15.3	11.6	49160	224	4.8	3
	2020	9	14	16:20	1	1016.3	82	0	14.8	11.9	47250	218	4.5	3.3
	2020	9	14	16:30	1	1016.3	84	0	14.6	12	48670	216	4.8	3.5
Suvilahti 1	2020	10	2	11:50	0	1022.6	63	0	15	7.9	32350	76	11.3	6.9
	2020	10	2	12:00	0	1022.6	64	0	15.1	8.3	35920	76	10.9	5
	2020	10	2	12:10	0	1022.6	64	0	15	8.3	32290	82	11.1	6.3
Suvilahti 2	2020	10	13	13:30	5	1015.3	67	0	10.9	5	50000	206	4.2	2.9
	2020	10	13	13:40	7	1015.4	66	0	10.8	4.8	50000	219	3.8	2.3
	2020	10	13	13:50	7	1015.5	65	0	10.7	4.4	50000	220	3.4	2.4
	2020	10	13	14:00	7	1015.6	68	0	10.3	4.6	50000	210	4.4	3
	2020	10	13	14:10	7	1015.7	70	0	10.1	4.8	50000	238	2.8	1.7
	2020	10	13	14:20	7	1015.8	69	0	10	4.6	50000	229	2.6	1.6
	2020	10	13	14:30	5	1016	70	0	9.7	4.5	50000	219	2.7	1.9
	2020	10	13	14:40	5	1016.1	73	0	9.4	4.9	50000	252	2.9	2.1

Viikki	2020	11	5	12:00	7	1005.6	73	0	9	4.4	50000	245	16.4	10.7
	2020	11	5	12:10	7	1005.7	73	0	9	4.5	45110	247	15.7	9.7
	2020	11	5	12:20	7	1005.8	74	0	8.9	4.5	48690	250	16.4	10.8
	2020	11	5	12:30	7	1005.6	74	0	8.8	4.5	50000	248	16	10
	2020	11	5	12:40	7	1005.6	74	0	8.8	4.5	50000	245	14.9	8.7
	2020	11	5	12:50	7	1005.6	74	0	8.8	4.4	50000	240	16.1	10.3
	2020	11	5	13:00	7	1005.4	74	0	8.8	4.4	50000	240	14.5	8.6
Kyläsaari	2020	11	6	11:20	1	1015.4	69	0	10.5	5.2	44850	273	8.7	5.1
	2020	11	6	11:30	1	1015.5	68	0	10.9	5.3	41900	274	8.3	4.7
	2020	11	6	11:40	1	1015.3	68	0	11	5.3	45930	269	8.9	4.7
	2020	11	6	11:50	5	1015.6	70	0	10.8	5.5	48520	266	9.1	6
	2020	11	6	12:00	5	1015.6	70	0	10.9	5.7	50000	264	10.4	4.6